Diffraction-based techniques for high contrast x-ray imaging

Lubna Naseem Peerzada

University at Albany, State University of New York, lp154545@albany.edu

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Diffraction-Based Techniques For High Contrast X-ray Imaging

by

Lubna Naseem Peerzada

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Dear Divine Creators I thank you for the sun, the moon, the stars and the universe. Please grant us the competence to understand the facts and to marvel the beauty of wondrous grandeurs of this universe, amen.
I dedicate this dissertation to my most adorable family:

Husband Ayub Qadeer Peerzada

Parents Shahnaz Rohi & Mohammad Naseem Khan

Grandparents, Haleema Khanum & Rustam Khan

Sister Sumbul Imran and her husband Sheikh Imran, children Annosheh and Abeer

Brother Khurram Naseem Khan and his wife Sadia Khurram, children Ahmed, Moezz and Noor-ul-Iman.
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Abstract

Two X-ray diffraction based techniques for high contrast were explored to improve contrast in radiology: diffraction enhanced imaging (DEI) and coherent scatter imaging.

DEI produces contrast in images based upon the difference in the X-ray refractive indices of materials or tissues. Two DEI systems were devised. Both were comprised of a conventional polychromatic copper X-ray source, polycapillary collimating optics and two silicon crystals. Lucite step phantoms and nylon tubing were imaged. No fringe effects were observed. The lack of observable edge enhancement may have been due to the optic structure which obscured refraction effects. Better results might have been achieved if a higher resolution detector or phantom of larger step size or larger diameter thin walled tubing had been used.

The second technique was coherent scatter X-ray imaging. The purpose of this work was to differentiate between healthy and diseased human breast tissues. For instance, breast carcinoma is known to have a peak coherent scattering angle at 12.2° for Mo Kα radiation at 17.5 keV, whereas fatty tissue peaks around 9°. A system which would be compatible with screening mammography was developed. The system was expanded to include sample scanning to allow for a larger image area. The modulation transfer function was computed for static and scanned images of a resolution phantom. These showed good agreement, indicating that the scanning was properly aligned and timed. Static and scanned images of phantoms were taken and the contrast was calculated for a series of experimental parameters including, grid tilt angle.

A complex phantom was also then imaged. It was possible to distinguish tissue-equivalent phantom types. Good contrast resolution scanned images were obtained which is promising for a diagnostic system.
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6. Summary
Chapter 1 Introduction

Breast cancer is the leading cause of preventable cancer death in women. According to a report by the American’s cancer society about 1 in 8 (12 %) of women in the US develop invasive breast cancer during their lifetime. The most common method currently available for detection is X-ray mammography. This technique is relatively successful but it is not the final solution for diagnosis. False diagnosis is common due to poor contrast between healthy and diseased tissues in the mammogram. A small difference in the attenuating properties of the tissue types leads to small differences in the grey levels of the mammogram; this leads to either cancers being missed or a false positive, with a biopsy of non-diseased tissue.

Two techniques were explored in this work to improve contrast in radiology; coherent scatter imaging and diffraction enhanced imaging (DEI).

In DEI a refractive index imaging system is used which is a combination of a source, a collimating optic and double diffraction crystals. The purpose was to obtain contrast in images based upon the difference in the X-ray refractive indices of materials or tissues, rather than relying on the differences in linear attenuation coefficients. In order to analyze a specimen through the (DEI) technique, the X-ray beam is made monochromatic by diffraction from a silicon crystal. As X rays pass through the sample, they refract at boundaries between different materials. After they exit the sample, the rays strike the second silicon crystal and then are diffracted onto the detector. This results in producing detailed images with contrast caused by X-ray refraction at the boundaries between tissues of specimen.

In our experiment Lucite step phantom and nylon tubing were imaged. Image gauge software was used to find out refraction bands at the edges.
The second technique was coherent scatter X-ray imaging. Coherent scatter is usually discarded in radiography along with Compton scatter. Coherent scatter, which is dominant at low angles, carries information about the molecular structure. The low angle X-ray scatter signature of a normal breast tissue is different from that of diseased tissue.

In our experiment an anti-scatter grid was used to collect scatter from graphite, which was used as a surrogate for carcinoma, and from beef fat, which is equivalent to normal tissue. The contrast was calculated as a function of experimental parameters including grid tilt angle.

There are six chapters in this dissertation. Chapter 2 introduces the physics of X-ray imaging. Chapter 3 discusses the experimental equipment. Chapter 4 describes monochromatic and refractive contrast X-ray Imaging (DEI) with polycapillary optics at 8 keV. Two DEI set-ups were designed in this work. The Lucite step phantom and nylon tubing were imaged; the data is analyzed in image gauge software and Excel program for visual refraction effects at the boundaries of specimen.

Chapter 5 provides details of coherent scatter mammography imaging work. The purpose of this work is to explore whether a screening mammography system can be designed to exploit coherent scatter to provide some tissue type information. A slot scan mammography system is designed and the static images of a graphite-fat phantom were obtained at angles from 9° to higher angles 18°, the contrast for each of these images was calculated and drew versus grid tilt angle (degrees). The system built for the coherent scatter experiment was also meant to do scanned images of larger objects. The scanning speeds of the stages for sample holder and that for the image plate were set based upon the magnification factor of our imaging system. The measurements demonstrated that there is potential to add tissue typing to screening.
mammography. Chapter 6 is a summary of all the work. For the first time, an imaging system capable of distinguishing tissue types for large specimens that is compatible with screening mammography was demonstrated.
Chapter 2  Physics of X-ray Imaging

2.1 Properties and Production of X rays

X rays are electromagnetic radiation having wavelengths roughly within the region from 0.005 to 10 nm.\(^1\) Two types of X rays are emitted from X-ray tubes, characteristic and continuous.

2.1.1 The X-ray Tube

A schematic diagram of an X-ray tube is shown in Figure 2.1.

![Schematic diagram of an X-ray tube.](image)

The X-ray tube has two electrodes. The negatively charged cathode is a filament that acts as the electron source. The positively charged anode contains the metal target. The electrons which are emitted from the cathode are accelerated by a high potential applied between the cathode and the anode. The X-ray spectrum from a Molybdenum source is shown in figure 2.2. There is K\(\alpha\) at 17.5 keV, and K\(\beta\) at 19.5 keV. Due to presence of copper in and near the anode the Cu K\(\alpha\) and K\(\beta\) peaks at 8.1 keV and 8.9 keV are evident in spectrum.
2.1.2 Characteristic X rays

Characteristic X rays are produced when the electrons of atoms in the target material make transition between allowed energy states. When impact by high energy electrons causes the ejection of an electron, the atom is left in high energy state. As an example, if a vacancy in the K-shell with principal quantum number $n = 1$ is filled by an electron in L-shell (with $n = 2$), the excess energy can be removed by the emission of a characteristic $K_{\alpha}$ X ray. But if the K-shell vacancy is filled by an M-shell electron ($n = 3$) instead, the transition gives a $K_{\beta}$ X ray. L and M shell vacancies result in emission of L and M characteristic X rays.

2.1.3 Bremsstrahlung X rays

Bremsstrahlung X rays are produced when the high energy electrons lose energy in passing through the Coulomb field of a nucleus. The bremsstrahlung X-ray spectrum generated by
electrons in an X-ray tube is characterized by a short-wavelength $\lambda_{\text{min}}$ that corresponds to the maximum energy of the excited electrons, so that

$$\lambda_{\text{min}} = \frac{hc}{E_{\text{max}}} = \frac{12.4 \text{ keV. } \AA}{(eV_o)}$$

(2.1)

where $h$ is Planck’s constant, $c$ is the velocity of light, $e$ is the electron charge and $V_o$ is the voltage applied to the tube.

### 2.2 Absorption Contrast

In conventional radiography, X rays pass through an object, and the resulting shadow image is recorded on a detector. The contrast in the images is generated by the different attenuating power of materials in the sample. Medical diagnosis often relies on radiographs. They are low cost and are easy available and relatively harmless. Conventional imaging is particularly effective in detecting high density objects in low density materials. However, it is less effective if the objects to be imaged have similar density. In figure 2.3, X-rays emitted from an X-ray source with intensity $I_o$ fall on a low density object of thickness $d$. There is another object inside this object with a different density. X-rays pass through both objects and are collected on to a detector.
Figure 2.3. Schematic diagram of conventional radiography.

If $I_1$ is the intensity of X rays behind object 1 with thickness $d$, then

$$I_1 = I_0 e^{-\mu_1 d},$$

(2.2)

where $\mu_1$ is the linear attenuation coefficient of object 1.

The intensity behind object 2 is then

$$I_2 = I_0 e^{-\mu_1 (d-t)} e^{-\mu_2 t},$$

(2.3)

where $\mu_2$ is the linear attenuation coefficient of object 2 of thickness $t$. Contrast is the normalized difference in intensities,

$$C = \frac{I_1 - I_2}{I_1} = \frac{I_0 e^{-\mu_1 d} - I_0 e^{-\mu_1 (d-t)} e^{-\mu_2 t}}{I_0 e^{-\mu_1 d}} = \frac{I_0 e^{\mu_1 d} (1 - e^{-(\mu_2 - \mu_1) t})}{I_0 e^{\mu_1 d}}$$

(2.4)

$$= 1 - e^{-\Delta \mu t}$$

(2.5)
If the contrast is small then

\[ C \approx 1 - (1 - \Delta \mu t) = \Delta \mu t. \]  \hspace{1cm} (2.6)

### 2.3 Refraction And Reflection

For X rays, the index of refraction is given by

\[ n = 1 - \delta + i\beta, \]  \hspace{1cm} (2.7)

where \( \delta \) is of the order of \( 10^{-6} \), \( \beta = \frac{\mu}{2k}, \ k = \frac{2\pi}{\lambda} \) and \( \mu \) is the mass absorption coefficient of the material. The value of \( \beta \) is much smaller than \( \delta \). The real part of the index of refraction for X rays is less than unity \(^4,5,6,7,8\) and depends upon the plasma frequency of the incident wave. It is approximated as

\[ 1 - \delta = \sqrt{1 - \left(\frac{\omega_p^2}{\omega^2}\right)}, \]  \hspace{1cm} (2.8)

where \( \omega_p = \left(\frac{N e^2}{m c_0}\right)^{\frac{1}{2}} \) is the plasma frequency of the material, \( N \) is the electron density of the material, \( e \) and \( m \) are the charge and mass of the electron, and \( \omega \) is the X ray photon angular frequency. \(^5\)

### 2.4 Refraction Contrast

Because the real decrement \( \delta >> \beta \), imaging based on differences in refractive index can have much higher contrast than conventional imaging. In diffraction enhanced imaging, the contrast is generated by refraction at the boundaries between tissues \(^8\), which provides a marked edge.
enhancement effect. The technique that employs an analyzer crystal,\(^9\) as shown in figure 2.4, to differentiate is called diffraction enhanced imaging (DEI).

![Figure 2.4 Schematic of Diffraction Enhanced X-ray Imaging Experiment.](image)

The deflection due to refraction can be analytically calculated for two geometries, a step phantom and a cylindrical object.

### 2.4.1. The Quantitative Calculation of Refraction of A Step Phantom

Using Snell’s law the relationship between the angle of deflection and the angle of incidence of X rays with the step phantom can be derived.\(^10\) Figure 2.5 shows the geometry of a step phantom.

The angle of incidence is \(\varphi_{\text{in}}\), \(n_1\) is the index of refraction of step phantom and \(n_2\) is equal to 1 for air.
Figure 2.5. The step phantom for refractive contrast measurements.\textsuperscript{10}

The ray incident on the bottom of the vertical face is deflected a distance $w$ compared to one incident at the top. The distance $w$ can be computed from the refracted angles.

From Snell’s law at the step face,

$$n_1 \sin(90^\circ - \varphi_{\text{in}}) = n_2 \sin \varphi_2 .$$  \hspace{1cm} (2.9)

where $\varphi_{\text{in}}$ is defined from the normal and $\varphi_2$ from the surface. Since $n_1$ is defined as air, $n_1 = 1$,

$$\sin(90^\circ - \varphi_{\text{in}}) = n_2 \sin \varphi_2 .$$  \hspace{1cm} (2.10)

At the bottom interface Snell’s law gives

$$n_2 \sin(90^\circ - \varphi_2) = n_1 \sin \varphi_{\text{out}} .$$  \hspace{1cm} (2.11)

Using the trigonometric identities

$$\sin(90^\circ - \varphi) = \cos \varphi \quad \text{and} \quad \cos \varphi = \sqrt{1 - \sin^2 \varphi} ,$$

Equation (2.10) and (2.11) become
\[
\sin \phi_{\text{out}} = \sqrt{\left(\frac{n_2}{n_1}\right)^2 - \cos^2 \phi_{\text{in}}} .
\] (2.12)

Using equation (2.8) for the index of refraction, \( \left(\frac{n_2}{n_1}\right)^2 = \frac{(1-\delta)^2}{1} \approx 1 - 2\delta \).

\[
\sin \phi_{\text{out}} \approx \sqrt{1 - \cos^2 \phi_{\text{in}} - 2\delta} = \sqrt{\sin^2 \phi_{\text{in}} - 2\delta}
\] (2.13)

\[
\approx \sin \phi_{\text{in}} \sqrt{1 - \frac{2\delta}{\sin^2 \phi_{\text{in}}}}
\] (2.14)

\[
\approx \sin \phi_{\text{in}} \left[1 - \frac{\delta}{\sin^2 \phi_{\text{in}}} \right]
\] (2.15)

\[
\approx \sin \phi_{\text{in}} - \frac{\delta}{\sin \phi_{\text{in}}}
\] (2.16)

The deflection angle \( \Delta \phi \), is defined as

\[
\Delta \phi = \phi_{\text{out}} - \phi_{\text{in}} .
\] (2.17)

Using \( \cos \Delta \phi \approx 1, \sin \Delta \phi \approx \Delta \phi \), then

\[
\sin \phi_{\text{out}} = \sin (\phi_{\text{in}} + \Delta \phi) \approx \sin \phi_{\text{in}} + \Delta \phi \cos \phi_{\text{in}} .
\] (2.18)

Comparing equation (2.15) with (2.17),

\[
\Delta \phi \approx \frac{-\delta}{\sin \phi_{\text{in}} \cos \phi_{\text{in}}} = \frac{-2\delta}{\sin 2\phi_{\text{in}}} .
\] (2.19)

For the refraction to be greater than the rocking curve width of the crystal, \( \Delta \theta \),

\[
|\Delta \phi| = \left|\frac{-2\delta}{\sin 2\phi_{\text{in}}}\right| > \Delta \theta .
\] (2.20)
Since for the required small incidence angle, \( \sin 2\varphi_{in} \sim 2\varphi_{in} \), this gives

\[
\varphi_{in} < |\Delta \varphi| = \left| \frac{\delta}{\Delta \theta} \right|. \tag{2.21}
\]

From equation (2.20) the refractive contrast is very sensitive to the incident angle \( \varphi_{in} \), so \( \varphi_{in} \) should be small to have refraction greater than the crystal rocking curve width. However this is not sufficient. The width of the band over which the reflection effect is seen, w, must also be larger than the pixel size P of the detector. The width is given by w \( \sim d \varphi_{in} \). The combined requirement is \( \frac{P}{d} \leq \varphi_{in} \leq \frac{\delta}{\Delta \theta} \), where d is the step size.

2.4.2. The Quantitative Calculation of Angular Spread of a Cylindrical Geometry

For an X-ray beam impinging on a cylindrical object of radius r, there is refraction at each boundary y, as shown in Figure 2.6.\(^{11}\)

![Figure 2.6. Refraction causes the X-ray deflect by an amount \( \Delta \theta \).](image_url)

From figure 2.6

\[
\sin \theta_1 = y/r . \tag{2.22}
\]
The ray enters horizontally from the left, so the deflection after traversing the sphere is $\Delta \theta$. This is found from calculating $\theta_3$ and $\theta_4$, since

$$\theta_4 = \theta_3 + \Delta \theta \quad . (2.23)$$

Because $\theta_1$ and $\theta_3$ are both related to $\theta_2$ by Snell’s law,

$$\theta_3 = \theta_1 \quad . (2.24)$$

The angle $\theta_4$ is given by

$$\theta_4 = \theta_3 + \Delta \theta = \theta_1 + \Delta \theta \quad , (2.27)$$

so the deflection is

$$\Delta \theta = 2(\theta_2 - \theta_1) \quad . (2.28)$$

Thus, defining

$$\theta_2 = \theta_1 + \Delta \theta/2 \quad (2.29)$$

and using Snell’s law at the entrance

$$n_1\sin\theta_1 = n_2\sin\theta_2 \quad , (2.30)$$

And, since $n_1 = 1$ for air and $n_2 = 1 - \delta$ for the cylinder, from equation (2.28) and (2.29)
\[
\sin \theta_1 \approx (1 - \delta)[\sin \theta_1 + \frac{\Delta \theta}{2} \cos \theta_1].
\] (2.31)

Thus
\[
\delta \sin \theta_1 \approx \frac{\Delta \theta}{2} \cos \theta_1.
\] (2.32)

Finally,
\[
\Delta \theta = 2 \delta \tan \theta_1.
\] (2.33)

To see the refraction effect, one needs \( \Delta \theta \geq \) the angular bandwidth of the crystal, i.e. the change in angle must be larger than the Darwin width accepted by the crystal so that the ray will not diffract. To achieve that one needs
\[
\tan \theta_1 \geq \frac{\Delta \theta}{2\delta}.
\] (2.34)

**Figure 2.7.** Refraction would be observed if \( w > \) pixel size.

Since \( y = r \sin \theta_1 \), this means rays are deflected to an angle too large to be diffracted from the second crystal if \( r - y \) is small.
Defining

\[ \theta_1 = \pi/2 - \varepsilon, \]  

(2.35)

then

\[ \tan \theta_1 \approx \frac{1}{\tan \varepsilon}. \]  

(2.36)

X-rays refract at the the boundary of the sample; if the angle of deviation lies in the acceptance angular range of analyzer crystal, those x-rays will be Bragg diffracted otherwise rejected. Due to this phenomenon a high contrast image is produced onto the detector which shows enhancement of edge, the width of this enhancement band is called the refraction band.

The requirement that the refraction band has a width greater than the pixel size \( P \) means that

\[ w = r - r \cos \varepsilon > P. \]  

(2.37)

so that

\[ r > \frac{P}{1 - \cos \varepsilon}. \]  

(2.38)

2.5 X-ray Diffraction Bragg’s Law

Diffraction occurs when scattered X rays from parallel planes interfere. Constructive interference of the X-ray radiation from successive planes occurs when the path difference is an integral number of wavelengths, as shown in Figure 2.8,

\[ n\lambda = 2d \sin \theta, \]  

(2.39)

where \( n \) is the order of diffraction, \( \lambda \) is the wavelength of X rays used, \( \theta \) is the angle of incidence and \( d \) is the inter atomic spacing.
The d spacing of the plane can be calculated from the crystal structure. An orthorhombic crystal is defined by a set of 3 translation vectors, $\mathbf{a}_x$, $\mathbf{a}_y$, and $\mathbf{a}_z$ in x, y and z directions.

For a cubic crystal with lattice constant a, these translation vectors can be written as

$$\mathbf{a}_x = a \hat{x}, \quad \mathbf{a}_y = a \hat{y}, \quad \text{and} \quad \mathbf{a}_z = a \hat{z}.$$  

(2.40)

The three co-ordinates required to represent the orientation of a crystal plane, the Miller indices (hkl), denote a single plane or a set of parallel planes in real space.

In cubic systems, including BCC, FCC, and diamond cubic structures, the spacing between two consecutive planes is

$$d_{hkl} = \frac{a}{\sqrt{h^2 + k^2 + l^2}}.$$  

(2.41)

where a is the lattice constant of the crystal.
2.5.1 Structure Factor

The total scattering amplitude $F_G$ for a crystal depends upon the Fourier transform of the electron density $n(r)$

$$F_G = \int n(r)e^{-\imath G \cdot r} \, d^3r,$$

(2.42)

where $G$ is defined as the difference between incident and scattered wave vectors, \( G = K_{\text{incident}} - K_{\text{scattered}} \) (2.43)

If the crystal is described in terms of a lattice with vectors $a_i$ then the Fourier transform of electron charge density in equation (2.42) is only non-zero if $G$ is a reciprocal lattice vector,

$$G = h\mathbf{b}_1 + k\mathbf{b}_2 + l\mathbf{b}_3,$$

(2.44)

where the $\mathbf{b}_i$s are the basis vectors of reciprocal space, and $(hkl)$ are the miller indices of the particular set of planes. The $b$’s are defined such that

$$b_i \cdot a_j = 2\pi \delta_{ij}.$$

(2.45)

If a set of basis atoms is added to the crystal, the structure factor $S$ describes the amplitude and phase of a wave diffracted from crystal planes.

$$S = \sum_j f_j e^{-i\mathbf{G} \cdot \mathbf{r}_j} = \sum_j f_j e^{-2\pi\imath(hx_j + ky_j + lz_j)},$$

(2.46)

where $f$ is the atomic scattering factor and $\mathbf{r}_j$ is the position of the $j^{\text{th}}$ basis atom in the cell.

For diamond cubic crystals, such as silicon, the crystal structure is represented by two interpenetrating primitive face centered cubic lattices. Each cube has an 8 atom basis \{(0,0,0),
(0, 1/2, 1/2), (1/2, 0, 1/2), (1/2, 1/2, 0) + 4 more shifted by (1/4, 1/4, 1/4) at (1/4, 1/4, 1/4) (3/4, 3/4, 1/4), (1/4, 3/4, 3/4), (3/4, 1/4, 3/4) so that

\[
S(hkl) = f \{ (1+\exp-i\pi(k+l)) + \exp-i\pi(h + l) + \exp-i\pi(k+l)(1+\exp^{i\pi/2(h+k+l)}) \}.
\]  

(2.47)

In this case, e.g. the structure factor of the 200 planes is zero.

### 2.6. Polycapillary Optics

Polycapillary optics can be designed for a wide variety of X-ray applications including medical applications. Polycapillary optics are arrays of hollow glass tubes used to collect, focus, and redirect X-ray and neutron beams. Figure 2.9 shows the cross sectional view of a polycapillary fiber.

![Cross-sectional scanning electron micrograph of a polycapillary fiber](image)

**Figure 2.9** Cross-sectional scanning electron micrograph of a polycapillary fiber with 0.55 mm outer diameter and 50 μm diameter channels.

In polycapillary optics, the focused or collimated beam is obtained from overlapping of the X-ray beams passing through thousands of capillary channels rather than a single tube. For single-bore capillaries, X rays are transmitted down a curved hollow tube if the tube is small and bent gently enough to keep the angles of incidence less than the critical angle for total internal reflection \( \theta_c \). Typical channel sizes are between 2 and 12 μm. There are thousands of such fibers strung
through metal grids in order to produce a multifiber lens, such as is shown in figure 2.9. Polycapillary optics can control X-rays over a broad range of angles and energies and produce large area collimated beams for crystal analysis from divergent X-ray sources. More applications of polycapillary optics include in x-ray lithography, X-ray astronomy, diffraction analysis, X-ray fluorescence and medicine. 14
References


2 www.hitachi-hitec-science.com


10 DanHong Li, “Monochromatic X-Ray Imaging with Polycapillary and Doubly-Curved Crystal Optics” University at Albany, State University of New York, 2006


12 C. Suryanarayana, M. Grant Norton, X ray Diffraction; A Practical Approach, p.51


Chapter 3 Experimental Equipment and Preliminary Measurements

This chapter describes the source, detector and electronics used in the experiment.

3.1 X-ray Sources

X rays are generated in a vacuum X-ray tube, which includes an anode and a cathode as shown in Figure 3.2, an electron beam is focused, within vacuum, from a metal cathode which emits electrons towards a rotating anode. The electron beam emitted from the cathode is accelerated by the high voltage and hits the anode with high enough kinetic energy to cause X-ray emission. Photons are released of a wavelength characteristic of the metal used in the anode. For a copper anode X-rays with a wavelength of 1.54 Å are produced from the Kα transition. Bremsstrahlung photons are also produced. Their energy and intensity depend on the applied voltage, current and the anode material. The anode can be fixed or rotated to dissipate heat generated by the intense focused electron beam. The Center for X-ray Optics (CXO) has fixed anode sources (copper, molybdenum, and tungsten anode sources in sealed tubes) and two rotating anodes (with copper and molybdenum anodes). The main differences between the two kinds of sources are that the rotating anode systems run at much higher electrical power.

The diffraction enhanced imaging (DEI) measurements were performed with a copper rotating anode source. The coherent scatter mammography measurements were performed with a Mo-anode Oxford Ultra Bright Source.
### 3.1.1 Rotating Anode Assembly

The rotating anode assembly is the most complex source available at CXO. The anode material for this experiment was copper. The maximum voltage and current are 60 kV and 100 mA. Typical values of voltage and current that were used in this work were 50 kV and 60 mA. Figure 3.1 shows schematic of rotating anode X-ray tube.

![Schematic of rotating anode X-ray tube](image)

**Figure 3.1. Schematic of rotating anode X-ray tube.**

The rotating anode is kept under a vacuum of $10^{-6}$ torr with a turbo pump backed by a mechanical pump. A water circulator is required and a high power high voltage power supply. The anode rotates at roughly 3000 rpm, this increases the effective surface area of the anode and reduces the amount of power deposited per unit area per unit time.\(^1\)

The distance between the beryllium window and the source was measured to be $36.5 \pm 1$ mm. The distance measured between the beryllium window and the shutter outer panel was $27.5 \pm 1$ mm. This $64 \pm 2$ mm distance should be included while determining the true distance between the source and the optic if the optic distance is measured from the panel.
3.2 Spectroscopic X-ray Detectors

Before starting the experiment, the spectroscopy detectors with the associated electronics need to be calibrated using radioactive sources with known X-ray energies. Table 1 lists the energies of some of the radioactive sources available in the Center for X-ray Optics. When using a detector with good sensitivity calibrating with a few energy lines from one radioactive source such as $^{241}$Am is sufficient. For a detector with poor resolution two or three radioactive sources are desirable to give a larger energy range. The Automated Control Program (ACP) has four entries for calibration peaks.

<table>
<thead>
<tr>
<th>Source</th>
<th>Energy line (KeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{241}$Am</td>
<td>59.62</td>
</tr>
<tr>
<td>$^{109}$Cd</td>
<td>88.04</td>
</tr>
<tr>
<td>$^{57}$Co</td>
<td>136.47</td>
</tr>
</tbody>
</table>

Table 1  Radioactive source peaks emission lines. The paired lines tested for $^{241}$Am are $K_{\alpha}$ and $K_{\beta}$ which are too close to resolve.

3.2.1 Amptek Detector

The XR-100T-CZT detector manufactured by Amptek, Inc. shown in figure 3.3, is a semiconductor detector that does not need any liquid nitrogen maintenance. The detector is a Cd$_{0.9}$Zn$_{0.1}$Te crystal. It employs Peltier cooling and has its own amplifier. This amplifier has a built-in optional Rise Time Discriminator (RTD), which can be used to discard pulses with long rise times. These pulses arose from photons collected deep in the crystal and hence also have reduced total charge. Eliminating these pulses improves energy resolution at the cost of lower collection efficiency. The output end of the amplifier connects to the MCA with a BNC coaxial cable as shown in figure 3.2.
The gain on the amplifier changes the voltage range of the output spectrum. Typically a gain of 1.5 to 2.0 is enough to view a range of 0 - 60 keV.
3.3 Scintillation Counter

Most of the characterization of the collimating optics discussed in this thesis were done with the NaI(Tl) detector. The output of this optics is large so a wide window detector is needed to perform these measurements. This detector needs a separate pre-amplifier, which is connected with an MHV-BNC coaxial cable to the amplifier. Another SHV coaxial lead connects the detector to the high voltage power supply.

The NaI (Tl) detector has a high noise level which overlaps part of the characteristic peak for copper.

![Figure 3.4 Schematic of scintillation counter.](image)

The basic principle behind this instrument is the use of a material which emits visible light photons (scintillates) when photons are absorbed. Electrons promoted into an excited state emit a visible light photon when they fall to the ground state. The light produced from the scintillation process is transmitted through a clear window where it interacts with a photomultiplier tube, which produces electrons when light strikes it. These electrons are accelerated towards a series of plates called dynodes through the application of a positive high voltage. When electrons from the photocathode hit the first dynode, several electrons are produced for each initial
photoelectron hitting its surface. This “bunch” of electrons is then accelerated towards the next dynode, where more electron “multiplication” occurs. The sequence continues until the last dynode is reached, where the electron pulse is now millions of times larger than the number of photoelectrons produced at the cathode. At this point the electrons are collected by an anode at the end of the tube forming an electronic pulse. The pulse is amplified and the electrical output is measured.

3.4 Electronics with Associated Detectors

3.4.1 Multi-Channel Analyzer (MCA)

Data were collected with a multiple channel analyzer is a device which to adjust the spectrum. The Tennelec model PCA Multiport multi-channel analyzers (MCA) manufactured by Oxford, Inc. have three level knobs: a low level discriminator (LLD), a Zero, and an upper level discriminator (ULD).

The zero knob shifts the channel corresponding to zero volts. The LLD knob changes the voltage value below which pulses are not counted. Low voltage electronic noise signals appear on the lower energy end of the spectrum and can add to the dead time. This can be reduced by raising the LLD level. The ULD knob is almost never used because there are very few high-energy noise sources. Turning the ULD counter-clockwise removes the counts on the high energy side of the energy spectrum.

Dead time refers to the time after a pulse is received before the detector is ready to receive another pulse. It is expressed as a percentage value between the live - true time (the time the detector was active and clock true). The MCA displays the dead time automatically shuts off the pre-set live time is reached.
3.4.2 Pre-amplifier and Amplifier

The amplifiers used with the NaI detector also have a built-in rise time discriminator (RTD), which is similar to that of the amptek detector. The output end of the amplifier connects to the MCA with a BNC coaxial cable. The gain on the amplifier changes the output voltage hence channel # for a given pulse input. The amplifiers have coarse gain settings of 10, 20, 50, 100, and 500 with a fine gain knob. These gain settings are selected for each individual detector to view the energy spectrum of the X-ray source within the range of the MCA as displayed by the Automated Control Program (ACP).

3.4.3 Programmable Motion Controller and ACP

The optics and crystals are moved with computer-controlled actuators. The GPIB board (plugged into the computer bus) connects the Newport Programmable Motion Controller Model PMC 200-P to the computer. The motion controller has two axes; axis-1 is connected to one actuator and axis-2 is connected to the second actuator. Typically there are 5 or more actuators in experiments that can be plugged into these axes as needed.

The automated control program (ACP) was developed with a design option to handle 8 actuators with their individual names. The speed default value of 0.4 mm/sec is meant for 850 series linear actuators. Requesting too low a speed will cause the program not to move the actuator and the controller to beep. For rotational stages series-495 and 496, the speed level needs to be changed to 0.8°/s. For some rotational stages the location is not saved properly to the output file. Even if the angles are not saved, the counts are recorded by ACP but the rotational displacement data must be manually generated in the appropriate Excel or Origin column.
The ACP, written in visual C++, is installed on all computer terminals in all set-ups in CXO. It not only collects the counting data directly but also integrates the photon counts in a region of interest (ROI) for specified energy ranges. The menu or Keys F8 and F9 are used to start and end the ROI.

### 3.5 Phosphor Screen

A simple imaging detector is a yellow screen consisting of a thin layer of 1 - 10 μm of Phosphorous. The physical principle is the same as that of scintillation detectors such as NaI(Tl) and CsI (I or Na). This can be viewed by a video camera connected to a video screen. The connection between the video camera (“video out”) and the video screen (“video in”) is a simple BNC coaxial cable.

### 3.6 BAS-1800 Imaging Analyzer

The image plate is used to store the energy deposited by the x-ray photons. A schematic of the plate is shown in Figure 3.5.

![Image Plate Schematic](image.png)

Figure 3.5 Schematic of the image plate.  

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Photostimulated luminescence (PSL) is defined as the release of stored energy within phosphor upon stimulation of visible light on it. Figure 3.6 shows the luminescence mechanism of the image plate.

![Figure 3.6 shows the luminescence mechanism of the image plate.](image)

X-ray photons excite the electrons into the conduction band of the halogen and are trapped by the Eu dopant color center in the crystal. A red laser beam inside the image reader irradiates the plate. The red light excites the electrons out of the traps. The recombination of these electrons with holes produces blue light luminescence. This luminescent signal produced is in proportion to the number of trapped electrons, and hence it is proportion to the original X-ray signal. The Bio-imaging analyzer BAS1800 manufactured by Fuji Photo Film Co., Ltd. is used to scan the image plate. It is connected to a computer with BAS-1800 IP Reader software loaded on it. It can be scanned at 50, 100 or 200 μm pixel size resolution with a reading time of approximately 2.5 minutes. The X-ray images are analyzed using two FUJI programs called Image Gauge Version 2.54. The IP is said to be overexposed if the image after processing by BAS-1800 IP has the maximum Photo Stimulated Luminescence (PSL) level of 79.15 8. An X-ray image taken on IP grows faint exponentially with time when exposed to ordinary light. The IP is preferably
protected in a cassette after it is exposed before read in the image reader. After reading the IP, it needs to be erased with the IP Eraser BAS before the next exposure.
References

1. http://www.amptek.com/xr100cr.html


Chapter 4 Monochromatic and Refractive Contrast X-ray Imaging
with Polycapillary Optics at 8 keV

4.1 Introduction
Diffraction-enhanced imaging (DEI) is a X-ray imaging modality that differs from conventional
radiography in its use of refraction to produce high-contrast images with a much lower radiation
dose compared to conventional radiography contrast. Diffraction Enhanced Imaging (DEI) is a
radiographic technique that extracts contrast information from three phenomena: absorption;
refraction; and small angle scattering, as described in chapter 2 section 2.3 and figure 2.4. In a
DEI imaging system the incident beam is obtained through diffraction from the first crystal, and
then the second crystal acts as an analyzer for the beam transmitted through the object. This
beam is collected on to the detector.

In this work a diffraction enhanced imaging system was developed using a copper rotating anode
source and a polycapillary collimating optic. The refractive index varies as inversely
proportional to $(\text{Energy})^{-2}$ of the X-ray source, therefore it is advised to use copper source to
study thin phantoms such as histology samples. Previously the work has been done on Mo source
at 17.5 keV to study big step phantoms with thicker step size and cylindrical phantoms with
thicker walls.

Since X-rays intensity is considerably reduced upon reaching the detector after double diffraction
from the silicon crystals; a collimating optic is placed after the X-ray source, the optic yields a
quasi parallel incident beam which can be diffracted with high intensity from the first silicon
crystal. The optic is necessary to produce adequate intensity from a conventional source. The
crystal serves as a monochromator. It is aligned to produce Cu $K_{\alpha 1}$ monochromatic radiation
diffraction. The second silicon crystal serves as a beam analyzer. The images obtained in DEI are the outcome of X-ray refraction from the boundaries of object which causes the beam to be deflected outside the acceptance angle of the second crystal. The contrast in images is obtained due to the density differences at tissue boundaries.

Two experiments were performed in this work first using the collimating optic A076H9 and the Si (100) crystals, and then monolithic optic 3369 in combination with silicon (220) crystals. These crystals are approximately 10 cm wide. The schematic of the Diffraction Enhanced X-ray Imaging set-up is shown in Figure 4.1

![Figure 4.1 Schematic of Diffraction Enhanced X-ray Imaging System (DEI).](image)

The Cu source produces a low energy $K_\alpha$ line, so the system is designed to extend the techniques of diffraction enhanced imaging to thin specimens for histology and non-destructive analysis at 8.1 keV. The higher energy systems previously demonstrated would not show much contrast for very thin specimens. The sodium iodide (NaI) detector described in Chapter 3 was used to measure the spectrum from the Cu source, the transmission of X-rays through the optic, and the
alignment of the crystal. The calibration of the detector was done using a radioactive Americium 241 source. The images were taken on image plates, read with 50 µm pixel size and analyzed in image gauge software.

4.2 Diffraction Enhanced Imaging (DEI) Set-up with Optic A076H9 and Silicon Crystals (100)

4.2.1 Alignment with respect to Cu X-ray Source

The experiment started with the alignment of metal washers with respect to the Cu X-ray source to determine the path of X-ray beam. This was a crucial step required to locate the path of the X-ray beam and also to determine where the beam from Cu source was the most intense. A series of X-ray images were taken with washer one in the beam as shown in figure 4.2. The washer was translated laterally in two dimensions until it was located in the brightest part of the beam. Then washer two was placed farther away from the X-ray source. The washer was translated until the second washer was concentric inside the first one as shown in Figure 4.3.

![Figure 4.2](image)

Figure 4.2 The schematic of laser alignment with respect to X-ray source.
Figure 4.3 The concentric image of the first washer inside the second one confirms the alignment of X-ray beam.

A laser was aligned so that it passed through the center of both washers and hit the center of Cu source window.

The laser was mounted on a kinematic stage so it could be removed from the beam and replaced with high accuracy.

4.2.2 Alignment of Collimating Optic (A076H9)

A large area multifiber optic A076H9 was employed to produce a large area beam. It is shown in Figure 4.4. The characteristics of the optic are shown in table 1.

Figure 4.4 Optic A076-H9 physical appearance.  

The setup is shown in figure 4.5 and 4.6. A lead shield with an opening slightly bigger than the size of the output optic was placed to reduce the background scatter. In addition, a lead
collimator was also placed after the beryllium source window to further reduce the scatter. The openings at the input and the output were bigger than the beryllium window.

A small phosphor screen, camera and video monitor were used to assist alignment. The fluorescent screen was placed beyond the optic and the image was viewed on the monitor.

Figure 4.5 displays the complete alignment set-up of the optic A076H9 with lead shield installed.
Figure 4.6  Schematic of Transmission measurement equipment.

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Optic A076H9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (mm)</td>
<td>127</td>
</tr>
<tr>
<td>Input Area (mm$^2$)</td>
<td>$8.07 \times 8.07 = 65.12$</td>
</tr>
<tr>
<td>Output Area (mm$^2$)</td>
<td>$10 \times 10 = 100$</td>
</tr>
<tr>
<td>Focal Distance (mm)</td>
<td>250</td>
</tr>
<tr>
<td>Fiber outer Diameter (µm)</td>
<td>510</td>
</tr>
<tr>
<td>Channel Diameter (µm)</td>
<td>10</td>
</tr>
<tr>
<td>Acceptance Angle (°)</td>
<td>1.8</td>
</tr>
</tbody>
</table>

Table 1 shows the characteristics of the optic A076H9 used in experiment.

The optic alignment system had three degrees of freedom, translational axes in the x, y and z directions. The actuators along these axes were connected to the motion controller which in turn was connected to the computer, and controlled through the lab’s ACP software. First the optic was placed slightly closer to the source than the expected focal distance, and the intensity through the optic was maximized by slight displacement of the optic in x and y directions. It is equivalent to rotating the optic in the beam. Then a scan was performed of the intensity as the
optic was moved in the direction perpendicular to the optic axis. Horizontal and vertical scans at a series of source - to - optic distances are shown in figure 4.7 and 4.8. As the source- to- optic distance approaches the focal point the scan narrows and the intensity increases. The scan files were plotted in the software “Origin”, which has a Gaussian fitting function. The horizontal and vertical scans at the focal distance are shown in figure 4.8, these scans look more symmetrical and yields higher intensity compared to scans shown in figure 4.7. The full width half maximum (FWHM) was calculated by multiplying the Origin software parameter \( w \) by \( \sqrt{2 \ln 2} \), as Origin uses \( G(x) = G_c e^{-\frac{2x^2}{w^2}} \) so that when \( x = \frac{w}{\sqrt{\ln 2/2}} \), \( G = 1/2G_c \). The full width half maxima (FWHM) were plotted versus distance, and are shown in figure 4.9. The acceptance angle, defined as FWHM/Distance between source and optic, was plotted as a function of the source distance in figure 4.10. The focal distance is 241 mm, where the acceptance angle is minimized. The distances given in figure 4.9 and 4.10 are the sum of the measured distance from the outer face of the source and the known 65 mm internal distance from the source to the window. The minimum scan width was 0.79 ± 0.06 mm.

The expected width in moving the optic past the source can be estimated from the sum of the source width, the fiber width, and the lateral distance the ray can travel after leaving the fiber. The fiber width matters because the channels in each fiber are parallel to each other. The lateral range is proportional to the distance and the critical angle, \( \theta_c \). Thus, \( \text{FWHM} = d + s + (1.3\theta_c) f \), where \( d \) is the fiber diameter of 0.3 mm, \( s \) is the source diameter, about 0.1 mm, and \( f \) is the input focal length. The 1.3 would be two if all rays up to \( \pm \theta_c \) reflected, and is a function of photon energy for real materials.
The expected scan width was 1.6 mm at 8 keV and 0.8 mm at 20 keV. Because the latter is closer to the measured value, the measurement was dominated by the high energy photons.
Figure 4.7 (a), (b), (c) Vertical scans of optic A076H9 at 20 kV and 10 mA at distances of 205 mm, 225 mm and 245 mm from the source. The lines are Gaussian fits. The measured FWHM are 0.90 mm, 1.02 mm and 1.36 mm respectively.
Figure 4.8 (a) Horizontal scan of optic A076H9 at 20 kV and 10 mA, the line is Gaussian fit performed in origin software, the FWHM measured is 0.79 mm.

Figure 4.8 (b) Vertical scan of optic A076H9 at 20 kV and 10 mA, the line is Gaussian fit performed in origin software, the FWHM measured is 0.73 mm.

Figure 4.9 The plot of FWHM (mm) vs. Distance (mm) between the X-ray source and the optic input.
Once the optic was aligned, an optic output image was checked for uniformity, this setup is shown in figure 4.11.
Slight displacements of the optic in the x, y and z directions were done to optimize the image. Using a small video camera and TV screen. A fluorescent screen was placed beyond the optic and the image on the screen was viewed by the video camera on the TV monitor. Once the optic was aligned an image was taken using the image plate, as shown in figure 4.12.

Once the optic was aligned an image was taken using the image plate, as shown in Figure 4.12.

![Image](image.jpg)

**Figure 4.12** displays the 1 cm$^2$ optic output taken with a Fuji image plate with the optic at the focal distance of 241 mm, with source voltage at 20 kV and a current of 10 mA for an exposure time of 30 seconds.

The software fit2D was used to import the file from an image plate format, and export into a format which could be read in excel, as shown in Figure 4.13 and 4.14.
Figure 4.13. The normalized output of the optic using fit 2D software; the inside structure of the optic is clearly visible.

Each hexagon in figure 4.13 shows the polycapillary fibers approximately 200 $^5$. Such fibers are strung through metal grids to produce a metal multifiber optic.

Figure 4.14. shows the X-ray intensity channels through the multi-fiber structure of the optic A076H9; this image was also obtained by using Fit2D and Excel software.
4.2.3 Transmission of Optic A076H9

The transmission of optic was determined by measuring the counts with and without the optic.

The counts with the optic were measured with the optic in its well aligned position while the counts without the optic were found out by moving the optic out of the beam. Figure 4.6 shows a schematic set-up to measure the counts with the optic in position.

The transmission of an optic was computed from the ratio of measured counts. The count rate without the optic is given by

\[ N = \frac{P}{4\pi L^2} A_{\text{detector}}, \]  

(4.1)

where \( P \) is the source X-ray emission rate, \( L \) is source - to - aperture distance, and \( A_{\text{detector}} \) is the area of the detector aperture.

Similarly, the count rate through the optic is given by

\[ N_{\text{output}} = \frac{P}{4\pi L'^2} A_{\text{optic}} T, \]  

(4.2)

where \( A_{\text{optic}} \) is the input area of the optic, \( T \) the transmission and \( L' \) is the source - to - optic input distance.

Thus the transmission of the optic was calculated

\[ T = \frac{N_{\text{optic}} L^2 A_{\text{(optic)}}}{N_{\text{output}} A_{\text{(detector)}} L'^2}. \]  

(4.3)
The resultant of transmission of optic A076H9 in the integrated energy range of 4 – 20 keV was 29 % ± 5% .

4.2.4 Alignment of First Silicon Crystal (400)

Diffraction enhanced imaging, as discussed in chapter 2, requires placing the sample between the two flat crystals. A (100) silicon diffracting crystal was used as first crystal, which serves as the monochromator.

To calculate the angle, the lattice constant of silicon was taken as 5.482 Å .

From Bragg’s law

\[ \lambda = 2d \sin \theta \quad , \]

(4.4)

where \( \lambda \) is the wavelength, \( d \) is the interatomic spacing, and \( \theta \) is the Bragg angle. The wavelength for the Cu K\( \alpha \) line at 8.1 keV can be calculated as

\[ \lambda = \frac{hc}{E} = \frac{12.4 \text{ keV Å}}{8.025 \text{ keV}} = 1.545 \text{ Å} . \]

(4.5)

The lower order (100), (200), (300) reflections have a structure factor of zero, \(^4\) as noted in chapter 2 section 2.4.

For the (400) reflection, the interplanar spacing \( d \) is given by equation (2.39) as

\[ d_{hkl} = \frac{a}{\sqrt{h^2 + k^2 + l^2}} = 1.375 \text{ Å} \quad , \]

(4.6)

where \( a \) is the lattice constant for Si, which was taken as 5.482 Å. \(^4\) Thus \( \theta_{K\alpha} \) is 34.44°.

The silicon crystal was placed approximately 10 cm from the exit of the optic, mounted on a Newport 495 rotation stage with a minimum angular step size of 0.005°.
The rotation stage zero angle was found by rotating the crystal until the laser just skims the surface the center of optic as shown in Figure 4.15.

**Figure 4.15.** Laser is shown skimming the first silicon crystal as the first step of its alignment.

The Si crystal was then rotated clockwise by the Bragg angle, 34°, for diffraction from the (400) plane. The detector was placed after the crystal as shown in figure 4.16. The crystal was then rotated until the counts were also maximized. The rotation scan is shown in figure 4.17.
Figure 4.16. The schematic of the aligned first Si crystal.

The plot was drawn in Origin software, fit to a Gaussian and the full width at half maximum was computed.

Figure 4.17. The rocking curve of the first silicon crystal. The FWHM obtained was $0.17^\circ = 3 \text{ mrad}$
The FWHM was 3 mrad, which is somewhat less than expected. The rocking curve after the optic should be largely determined by the divergence of the beam from the optic, which is expected to be larger than the critical angle at 8 keV, about 3.75 mrad.

The narrower width can be due to a low input divergence or to surface deflects which reduce the reflectivity of photons hitting at angles close to the critical angle. The alignment of the first and second silicon crystals is shown in figure 4.18. X-rays are shown being diffracted off from the first crystal to the second one.

![Figure 4.18. Left picture shows the optic output and right shows the diffracted (400) beam and reflections from other planes as well. For these a λ ≠ 1.54 Å for these, so they are just due to Bremsstrahlung, resulting in noticeably weaker beam. The (400) reflection appears as an elongated rectangle because the image plate was not perpendicular to the beam from the crystal.](image)

### 4.2.5 Alignment of Second Silicon Crystal (400)

For diffraction enhanced imaging, a second crystal was used as an analyzer to attempt to observe refraction in the object. Aligning the second crystal was the most difficult step as the range of angles that can be diffracted by the second crystal was very narrow.

The second crystal, along with the rotation stage, was mounted on a kinematic stage placed at 12 cm from the first Si crystal. In order to align the second crystal, the first Si crystal was rotated by
90° so that the laser, which had been aligned as designed in section 4.2.1. was reflected off of the first crystal onto the second Si crystal. The second crystal was then rotated until this laser light then reflected back to hit the laser aperture, as illustrated in figure 4.19 and figure 4.20.

Figure 4.19. The position of the two crystals when laser back reflection occurs. The first crystal is rotated to the dashed black line position.
Figure 4.20. The laser actual dot (lower one) and the back reflected dot on the upper side on the surface of first silicon crystal is shown, this step helps us to calibrate the position and angle of the second silicon crystal.

The second silicon crystal was then rotated back by (90° - Bragg angle) for (400) diffraction. The first silicon crystal was rotated by 90° back to its Bragg position. The second crystal was scanned to maximize the intensity. Because the width of the second rocking curve is very small, the step size is set as low as possible, at 0.005°, so even to scan a small angular range, it took more than an hour to detect the actual peak. The peak is shown in figure 4.21. Even after inserting the shields to reduce the background caused by the scatter, the background was very high, which made the alignment of the second Si crystal very difficult.
The width of the second rocking curve is dominated by the energy width of the characteristic line. The relationship between wavelength and angular range is obtained by differentiating Bragg’s law, so that

\[ \Delta \lambda = 2d \cos \theta \Delta \theta. \]  

(4.7)

Dividing equation (4.7) by \( \lambda = 2 \sin \theta \) gives

\[ \frac{\Delta \lambda}{\lambda} = \frac{\Delta \theta}{\tan \theta}. \]

(4.8)

The contribution to the rocking curve width from the K\(_{\alpha1}\) line width of \( \Delta E = 4 \text{eV} \) is

\[ \Delta \theta = \tan \theta \frac{\Delta E}{E} = 0.3 \text{mrad} \]

(4.9)
This is in good agreement with the measured width of 0.3 ± .02 mrad. The separation between the K$_\alpha$ doublet lines is 20 eV, much wider than the peak, so the second crystal was aligned to a single emission line. The intensity is much weaker than after the first crystal as the input beam now has a narrow energy width because it is restricted to a narrow angle. The scan in figure 4.21 was performed with a longer count time per point that was used for figure 4.17.

An image plate was placed after the second silicon crystal to obtain the optic output image, as shown in figure 4.22.

Figure 4.22. (a) Lens close-up shows the output from the second crystal after optic A076H9. It is cropped to show only the single 1 cm$^2$ diffracted beam. (b) A larger exposure showing the main intense (400) diffraction (circled), as well as diffraction from other crystallographic planes. The main reflection in (b) is rectangular rather than square because the image plate was not placed perpendicular to the diffracted beam. The image was taken at voltage 40 kV, and current 50 mA for 30 min.
Now the Diffraction Enhanced Imaging was aligned. The rotation stages on which the silicon crystals were mounted were then locked with their screws. The alignment of silicon crystals was very delicate and a slight tweak of finger could ruin the whole alignment of set-up. All actuators connected to the stages were also disconnected.

4.2.6 Step Phantom Measurements

The experimental system for diffraction enhanced imaging, sketched in figure 4.1 is shown in figure 4.23. The phantom was placed between the two crystals.

Figure 4.23. Diffraction Enhanced Imaging system (DEI) set-up ready for phantom images. The image of phantom 2.5 mm thick was taken at 40 kV and 50 mA with exposure time 30 min.
A step phantom is a test object that has an abrupt change in height. For a step phantom the relationship between the deflection angle and the angle of incidence was calculated in chapter 2 to be

\[
\Delta \phi = \frac{-2\delta}{\sin 2\phi_{in}},
\]

(4.10)

where \(\phi_{in}\) is the angle of incidence of X-ray beam, and \(\delta\) is the refractive index for Lucite, which is \(4.2 \times 10^{-6}\) at 8 keV.

A refraction \(\Delta \phi\) which is larger than the crystal rocking curve width \(\Delta \theta = 0.3\) mrad requires an incident angle \(\phi_{in} \left(\frac{\delta}{\Delta \theta}\right) = 0.7^\circ\). The expected width of the dark band in the image was also seen to be

\[
\Delta w = d \phi_{in},
\]

(4.11)

where \(\Delta w\) is the width of band that appears due to refraction contrast, and \(d\) is the step height.

For a step height of 1 mm, the angle would have to be larger than about 2.8° to give a \(\Delta w\) greater than pixel size of 50 µm.

A 2.5 mm thick step phantom, placed with a step height of 1 mm size was placed in-between the two silicon crystals, with the step edge at \(\phi = 2^\circ\) to the beam direction. It was exposed for 30 min. at 40 keV and 50 mA, giving the image shown in figure 4.24.
Figure 4.24. The image after the second silicon crystal with the step phantom between the first and second crystal. The left side has more intensity where the thickness of phantom is less, only the fiber structure can be seen no refraction effects. This image was taken at 40 kV and 50 mA for exposure time 30 min $\phi_{in} = 2^\circ$.

Figure 4.25. (a) Graph of interpolated phantom/Normalized output optic data vs. Distance (mm). Again, no refractive effects are visible.
The normalized intensity profiles were drawn versus distance for the output optic with no phantom and the one which has phantom in it. Both plots were drawn on the same axes for comparison, the red line (output optic phantom) shows that the intensity is diminished on the right side when the X-rays are obscured by the phantom.

![Graph of interpolated phantom/normalized output optic data vs. distance. No DEI is observed.](image)

Figure 4.25 (b). Graph of interpolated phantom/normalized output optic data vs. distance. No DEI is observed.

Figure 4.25 (b) only displays the fiber structure; the bending of X-rays around the edges of phantom or any fringe effect is not observed.

The optic output has significant background due to the fiber structure along the optic face as shown in the profile in figure 4.26 (a). The profile with the phantom also shown in figure 4.25...
(b), was shifted to give the best visual fit to the left side of the profile. The ratio was then taken to attempt to correct for the optic structure, with the result shown in figure 4.25 (b).

In Figure 4.25 (b) ripples are observed but it appears to be due to optic structure and not because of any refraction from boundaries of the sample. No DEI was observed.

4.2.7 Cylindrical Phantom Measurements

The step phantom was replaced with a thin tube. For the step phantom, the analyzer was set to the aligned position. Then if there is refraction, photons hitting the analyzer at angles other than the Bragg angle are not sent on to the detector. However, higher contrast can be achieved by rejecting the unrefracted photons. In that case, photons refracted by the sample into a different angle may be detected by rotating the analyzer crystal. Hence the second silicon crystal was placed at different positions on rocking curve and the images of thin tubing of diameter 2.8 mm were taken at peak position, and at about ± FWHM, and at ± 3FWHM. (The + FWHM was the low angle side.)
Optic output images (with no phantom) were also taken at different angles on both sides of rocking curve in order to compare images with phantom with no phantom. The intensity profiles at the peak position of second silicon crystal are shown in figure 4.27 (a). The tubing profile was shifted to match peaks of the optic image. Then the tubing phantom data was interpolated for the
shift and divided by the optic output data, as shown in figure 4.27 (b). The fiber structure makes it difficult to see whether there was edge enhancement.

Figure 4.27 (a). The normalized intensity profiles for output optic and tubing diameter 2.8 mm. Again the optic structure obscures any edge enhancement.

Figure 4.27 (b). The interpolated tubing data divided by optic output data.
The interpolated phantom data for four positions of the second crystal, at peak, at FWHM and at ± 3 FWHM, divided by the optic output data at the correspondence positions. The profiles are shown in figure 4.27 (c).

![Normalized Intensity vs Distance (mm)](image)

**Figure 4.27 (c).** The smoothed profiles for positions at peak, FWHM, ±3 FWHM. No edge enhancement was observed.

The multifiber optic had too much background structure which was a primary reason to switch to a monolithic optic. On the same X-ray source a new diffraction enhanced imaging set up was built using a monolithic optic and two different silicon crystals.

### 4.3. Monolithic Collimating Optic 3369

Monolithic capillary optics are shaped as a single piece so that no external frame assembly is required.
Monolithic optic 3369 has its input focal length at 250 mm from the Cu rotating anode source so the optic was placed at distance 185 mm from the Beryllium window. The optic was placed in an optic assembly designed especially to hold the optic and there was a lead piece having an opening slightly bigger than the optic input to reduce X-ray scatter background. The monolithic optic along with its assembly was mounted on a stage driven by Newport actuators in three dimensions as shown in Figure 4.29.
Figure 4.29. Collimating optic 3369 with lead aperture in its front, placed at 250 mm from Cu X-ray source.
The alignment was similar to that for optic A07H9. First optic 3369 was aligned making use of a video camera and TV monitor by moving the actuators in x – and y – directions. The NaI detector was brought into use to take scans in both x- and y directions. The scan data was imported from scan files into Origin software. In figure 4.30 scan plots at the focal point are shown. The intensity through the optic was maximum at the focal distance.

Figure 4.30 (a) Horizontal scan at 20 keV and 10 mA, FWHM = 0.74 mm.
Figure 4. 30. (b) Vertical scan of optic 3369 at 20 kV and 10 mA, FWHM 0.74 mm

The expected scan width is

\[ w = c + 1.3 (\theta c) f + s \]  \hspace{1cm} (4.12)

where \( c \) is the channel diameter, about 6 \( \mu \)m, and \( s \) is the source width. The expected width is 0.5 – 1 mm, for photon energies from 20 – 8 keV, in good agreement with the measurement.
Figure 4.31. (a) Output optic image at 20 kV and 10 mA for exposure time 10 seconds. (b) Visible light photograph of the optic, showing the hexagonal structure within the metal case.

Figure 4.31. (a) displays the X-ray output from the aligned optic. The image is circular and the upper half optic is slightly more intense than the lower half. (b) The visible light camera picture of optic shows the optic is hexagonal. The optic was translated closer to the X-ray source and away from it to see if the X-ray image of optic output looks hexagonal instead round. The image remained circular but the scan width was broadened. Apparently the corners of the optic did not transmit. Therefore the optic was brought back to its position at focal distance, 185 mm from the beryllium window. The intensity through the optic was the maximum at the focal distance.
4.3.1. Alignment of First Silicon Crystal (220)

From equation 4.9, $\Delta \theta = \frac{\Delta E}{E \tan \theta}$, a smaller Bragg angle will result in a narrower rocking curve for the second crystal, which should make the system more sensitive to refraction. For that reason (110) crystals, with a nonzero (220) diffraction, were substituted for the (100) crystals.

For this plane

$$d_{hkl} = \frac{a}{\sqrt{h^2 + k^2 + l^2}} = 1.94 \text{ Å},$$

so that the Bragg angle from equation (4.4) is $23.38^\circ$.

The silicon crystal was mounted on a Newport 495 - rotation stage and aligned as before.

Figure 4.32. (a) The Rocking curve of 1\textsuperscript{st} silicon Crystal, FWHM is 2 mrad. (b) Diffracted beam from (220) plane along with weaker reflections from other planes.
The aligned crystal rocking curve is shown in figure 4.32 (a). The width is considerably less than the critical angle. This is possible for a high quality optic if the source divergence, s/f, is small. In this case s/f is about 0.5 mrad. The output image is shown in figure 4.32 (b).

4.3.2 Alignment of Second Silicon Crystal (220)

After the second silicon crystal was roughly aligned, the rotation scan was done with 0.005° step size. It took an hour and a half to complete the scan. It was done at 40keV and 50 mA, the maximum at which the X-ray machine could be run. The output intensity from the second crystal is about 1/5\textsuperscript{th} of that from the first crystal despite the increase in current and voltage. The rocking curve of second silicon crystal is shown in figure 4.33 (a).

![Figure 4.33 (a) The rocking curve of second silicon crystal, FWHM = 0.33 mrad.](image)

![Figure 4.33 (b) Diffraction pattern from second silicon crystal at 40 kV and 50 mA, Exposure time = 30min.](image)
The expected width of the peak is 0.2 mrad, but the actual width is again 0.3 mrad. The efficiency $\eta$ of the second optic was calculated in terms of current, voltage and time taken into account,

$$\eta = \frac{C_{2nd}}{C_{first}} \times \frac{J_1 V_1^2 t_1}{J_2 V_2^2 t_2}$$  \hspace{1cm} (4.14)$$

where $C_{first}$ is the number of counts at peak in the scan of the first crystal, and $J_1, V_1$ and $t_1$ are the current, tube voltage and the time taken during the scan of first silicon crystal. Similarly $C_{2nd}$ is the number of counts at peak in the scan of the second crystal, and $J_2, V_2$ and $t_2$ are the current, tube voltage and the time taken during the scan of second crystal. The result was calculated in equation (4.14).

$$\eta = \frac{60 \times 10^3}{300 \times 10^3} \times \frac{20mA}{50mA} \times \frac{(20kV)^2}{(40kV)^2} \times \frac{10sec}{70sec} = 0.0028$$  \hspace{1cm} (4.15)$$

The value of efficiency calculated in equation (4.13) is in agreement with the imaging data, when instead of number of counts $C_{first}$ and $C_{2nd}$ at the peak position in scans are replaced by PSL values of both the crystals in images taken after the crystals and $t_1$ and $t_2$ are the exposure time.

$$\eta = \frac{PSL_{2nd}}{PSL_{1st}} \times \frac{J_1 V_1^2 t_1}{J_2 V_2^2 t_2}$$ \hspace{1cm} (4.16)$$

$$\eta = \frac{1.34}{17.52} \times \frac{20mA}{50mA} \times \frac{(20kV)^2}{(40kV)^2} \times \frac{600sec}{1800sec} = 0.0025$$ \hspace{1cm} (4.17)$$

A lead shield was placed between the optic output and the second crystal to avoid X-rays falling directly on the second crystal, to make sure that the beam received on the image plate was diffracted only by the second crystal.
Figure 4.34 shows the complete experimental set up for diffraction enhanced imaging.

![Figure 4.34. Experimental set-up for Diffraction Enhanced Imaging (DEI) at 8 keV with monolithic optic and silicon crystals (220).](image)

4.3.3 Phantom Images Calculations

The images of a phantom of thickness 2.5 mm and a thin tube were taken. Profiles of these images were analyzed. A thin tube, of external diameter 2.8 mm, was placed in the sample holder. The sample was located using a laser, which could be directed towards the sample by rotating the crystal by 90°, as described in figure 4.20. The image is shown in figure 4.35.
Intensity profiles were drawn in horizontal direction for lane width 50 across the images with and with out the tubing. Both intensity profiles were imported in excel software, the data was normalized and then plotted versus distance.

Figure 4.35. (a) X-ray image of thin tube at 40 kV and 50 mA for exposure time 30 min.

Figure 4.35 (b). Normalized intensity profiles for both images optic output and thin tubing.
The data was shifted to make the parts of the image outside of the tubing coincide. Finally the normalized data for tubing was divided by the normalized data of output optic, with the result shown in figure 4.35 (c).

![Graph obtained after division of normalized data for thin tubing by that of optic output.](image)

In Figure 4.35 (c) a dip shows the presence of thin tubing as the intensity is attenuated but no fringes could be observed in this region due to refraction from walls of tubing.

A Lucite phantom 2.5 mm was placed in between the two crystals at 2°. The X-ray image after the first silicon crystal is shown in figure 4.36 (a) and then after the second crystal in 4.36 (b).
After 2nd Si crystal at 40kV & 50mA; exposure time is 30min.

Figure 4.36. (a). Optic output image of Lucite phantom after first silicon crystal at 20 kV and 30 mA for 10 min. (b). Optic output image of Lucite Phantom after second silicon crystal at 40 kV and 50 mA for 30 min.

The beam after diffraction from second crystal was inverted. The expected width of enhancements band across edge was calculated $w = d\phi_{in} = 0.033$ mm which was difficult to see on a detector with 50 µm pixel size. An intensity profile of lane width 50 was drawn perpendicular to edge of phantom. The normalized intensity profiles were obtained as before in tubing data. The plots are shown in Figure 4.37 (a).
Figure 4.37 (a). Normalized intensity plots for optic and phantom vs. distance (mm).

The interpolated normalized intensity phantom data was divided by the normalized intensity data of output optic. The Excel smoothing function was applied to this divided data. A plot of the smoothed phantom data versus distance is shown in figure 4.37 (b).

Figure 4.37 (b). Data for perpendicular profile drawn to edge in phantom image.
No edge enhancement is observed.

Better results might be obtained with a high resolution detector, and thicker steps or large diameter thin walled tubing.
References

Medical application of diffraction enhanced imaging. Breast Dis 10 197–207


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Chapter 5  Coherent Scatter Mammographic Imaging

5.1 Introduction

Conventional mammographic imaging leads to low contrast\(^1, 2, 3\) as it relies on the small differences between the X-ray attenuation coefficients of healthy and diseased tissue. It has been observed that additional information on breast tissue type can be obtained from coherently scattered radiation from different tissue types which have different nano-scale structures and scatter at different angles.\(^3, 4, 5, 6, 7, 8\)

X-ray scattering during diagnostic examinations at high angles is predominately Compton scatter and multiple scatter dominate with little useful information. At lower angles, coherent scatter dominates because it is peaked in the forward direction. Constructive interference of the coherent scatter can be described using an effective Bragg’s law

\[
\lambda = 2dsin\theta
\]  

(5.1)

where \(\lambda\) is the wavelength of the x-ray radiation, \(d\) is an average spacing of the tissue structure that gives rise to the coherent scatter, and \(\theta\) is one quarter of the cone of the scattered radiation,\(^9\) as shown in Figure 5.1.

![Figure 5.1. Cone of coherent scatter radiation peaked at a characteristic angle 2\(\theta\).](image-url)
This says the intensity describes a circularly symmetric angular region around the axis of the primary beam. The rings are uniform if the crystallites have random orientation all around the beam axis, the degree of orientation of random crystallites can be found out by drawing a radius vector of the complete 3-dimensional diffraction pattern. Amorphous materials such as human tissue have broad diffraction peaks but are still characteristic of the particular material. Recently there has been some investigation of the potential to add scatter intensity information to computed tomography (CT) systems to provide additional structural information of tissue under investigation. In CT, separate images are taken from many angles and then these images are reconstructed to provide 3D images based on the attenuation coefficients of the object. The CT systems employ a narrow fan beam. The fan beam illuminates only a very narrow line so that the scatter in the out-of-plane direction can be easily measured. Then, instead of the usual 3D attenuation matrix, a 3D coherent scatter matrix is computed from criteria such as the intensity at a particular angle. This work has demonstrated the potential for the use of coherent scatter in tissue. However, CT imaging is expensive and requires a higher dose than simple radiography. It is not currently feasible for mammography population screening.
Figure 5.2. Schematic of wide slot scatter mammography. X rays (red color) impinge on the sample; X-rays which are diffracted (blue lines) from the sample pass the grid and finally are collected on to the detector area. The diffracted rays can be traced back to an apparent source (dashed lines). Placing a grid so it points at the apparent rather than the original source preferentially passes the diffracted beam.

The coherent scatter system in this work was designed to have the potential to add tissue typing to screening mammography with no increase in dose. It could work with a conventional slot scan mammography system to produce scatter images of abnormal breast tissue. The design described here uses the intensity of scatter at a characteristic coherent scatter angle as a measure of the presence of that tissue type. Since the scatter peaks for amorphous materials such as tissues are inherently fairly broad, high angular resolution is not required. Angular selectivity is achieved with a simple focused grid as shown in Figure 5.2 and 5.3.

In conventional radiographs scatter radiation can be removed by using a scatter rejection device called a grid. A grid consists of thin parallel strips of lead embedded in aluminum or plastic and aligned at an angle to the direct beam so that primary beam is blocked and only the scatter X-rays pass through and collected on to the detector, as shown in figure. 5.4. The grid is placed between the image plate and the phantom. Compton scatter is blocked by the lead strips,
thereby reducing scatter reduction. The grid performance is determined by the grid ratio, $r$, which is the ratio of the height of the grid $H$ to the width of the interspace $D$, as sketched in figure 5.3.

![Diagram of grid structure and function](image)

**Figure 5.3. Structure and function of grid**

$$r = \frac{H}{D}.$$  \hspace{1cm} (5.2)

The acceptance angle is then

$$\theta_g = \arctan\left(\frac{D}{H}\right) = \arctan\left(\frac{1}{r}\right).$$ \hspace{1cm} (5.3)

In the coherent imaging system, X rays are diffracted at the characteristic angle from each small volume element, which would make a set of diffraction rings on the image plate in the absence of the grid. The grid placed is at the characteristic angle so that only coherent scatter is collected on the image plate. Since the grid is placed at an angle, instead of collecting the entire diffraction cone from each volume element, only the portion from one side is transmitted onto the image plate. The final image is the sum of all signals collected from all volume elements. For a line of volume elements due to a slot beam on a uniform sample, the image appears as a vertical band on the image plate. The grid also functions to reduce the Compton scatter so that the signal is more evident.
The purpose of this work was to distinguish the coherent scatter of the breast cancer tissue from that of the normal fatty breast tissue since the characteristic angle of diffraction of a diseased breast tissue is different from that of a normal breast tissue.

**5.2 Experimental Design**

The main object of this work was to develop a system to employ coherent scatter to provide tissue typing information in a manner compatible with a conventional mammography system.

In this chapter the design and testing of the coherent scatter set-up and some results of coherent scatter measurements are presented. This work was built on earlier measurements performed by Wei Zhou in the CXO laboratory. His work shows good discrimination although there were some repeatability issues and only a small sample could be imaged.
Figure 5.5 shows the experimental setup. The whole setup was mounted on an optical rail.

Figure 5.5 Experimental setting for the coherent scatter measurements. X-rays originate from the source at left. The source is cooled with the fan at top. The rail is aligned to the x-ray beam. The phantom is placed in the sample holder and the image plate and grid are placed on the stages.

The source could be moved with five degrees of freedom: parallel to the rail (z axis), horizontal (x), vertical (y) and rotation about the vertical axis. The second rail was fixed to the rotation stage to hold the image plate and the grid for coherent scatter. The sample holder was also placed on a rail. The second stage for the image plate and the stage for the sample holder could be moved separately while scanning the phantom, with different speeds controllable through computer software.
5.3 Experimental Apparatus

This section includes the alignment procedure and steps necessary to build the experimental set-up for coherent scatter imaging measurements.

5.3.1 Oxford Apogee X-ray Source

A low power Oxford Apogee molybdenum X-ray source (Figure 5.6) was used for the test system in this work. The maximum voltage was 50 kV and the maximum current was 1 mA for the source, so the maximum output power was 50 W.

Figure 5.6. Molybdenum X-ray source.\textsuperscript{11}

While taking the coherent scatter images, the source was typically run at 47.5 kV and 0.95 mA, which was close to the maximum power.

5.3.2 X-ray Source Spectrum

The source spectrum measured with an Amptek Cd Te detector and Oxford MCA is shown in Figure 5.7. The spectrum shows some Cu contamination either from alloying of the anode or from the electron beam hitting copper rings outside the Mo target area. To make the source more monochromatic, and to produce sharper diffraction peaks, a 130 μm thick Zr filter was placed close to the output Be window of the source to absorb the Mo $K_\beta$ line. Figure 5.7 and 5.8 show the source spectra at 32 kV & 0.92 mA, with and without the Zr filter.
Figure 5.7 Mo source spectrum without Zr filter at 32 kV and 0.92mA.

Figure 5.8 Mo source spectrum with 138 µm Filter at the same voltage and current as in Figure 5.7. The Kβ is suppressed.

5.3.3 X-ray Source Stability

In order to find out the source warm up time and its stability, a scan was run for 1 hr. time using the ACP software and an Amptek detector, as shown in Figure 5.9. The source was run at 25kV and
0.1mA. Aluminum filters had been placed outside the beryllium window of X-ray source to avoid dead time.

The test showed that the source took 2 min. to warm up and then remained stable.

![Graph](image)

**Figure 5.9 Mo source scan test.** A low current was used to avoid saturating the detector.

The test showed that the source took 2 min. to warm up and then remained stable.

### 5.3.4 Alignment of X-ray Coherent Scatter Imaging System

This section describes the steps for the alignment of the equipment with respect to the Moly X-ray source. To select a portion of the beam which is intense and uniform, a washer was placed 5 cm from the Mo source, as shown in Figure 5.10 (a).
5.10 (a) Washer 1 was placed at 5 cm after Mo source.

An image was taken at 25 kV and 0.05 mA with exposure time 2 sec with the image plate, as shown in Figure 5.10 (b). The horizontal and vertical profiles of intensity vs. distance, drawn in image gauge software confirmed the uniformity of the beam within washer, as shown in figure 5.10. (c ) and (d).

(b) The pseudo color image of first washer in front of the source, taken at 25kV and 0.05mA

(b) Horizontal profile for the beam PSL vs. distance D (mm) through the center of the washer.
5.10. The alignment of first washer at 5cm from the Mo source.

Figure 5.11 (a) The second washer was placed 18 cm from the Moly source. The image is displayed on the right was taken at 25kV and 0.05mA for 30 seconds. The second washer appears concentric inside the first (b) The addition of a third washer is shown. The image taken was at 25kV and 0.05 mA for 75 seconds (c) The last washer 4 was 115 cm apart from the Mo source. The image shows the complete alignment of all four washers. Each seems concentric with the preceding one, as a useful tool to define the path of x-ray beam. The heights of all washers were 20.5 cm from the optical table.
Washer 2 was then placed after washer 1, as shown in figure 5.11, and aligned to the laser beam. The image is shown on the right in figure 5.11 (a). Then washer 3 was placed 85 cm from the source and aligned with respect to washer 2 and washer 1, with the image shown in figure 5.11 (b). Washer 4 was placed at 115 cm and aligned. The concentric image of all four washers is shown in Figure 5.11 (c). Finally, the laser was aligned to pass through all four washers, then hit the Mo source, as shown in Figure 5.12. After the laser was aligned with respect to the X-ray source all washers posts, which were bolted on kinematic mounts, were removed. They could be repeatably replaced as needed to check the alignment of the equipment.

![Figure 5.12. The alignment of laser with respect to Mo source.](image)

The laser alignment was always an important step in the experiment before the alignment of grid and stages take place.

### 5.3.5 Wide Slot Beam Collimation

To make the x-ray beam collimated, two lead sheets were installed as shown in Figure. 5.13 (a) and (b) to create a 6 mm wide, 80 mm long slot, placed at 430 mm from the source. The width of the slot was similar to the slot width of commercial scan slot mammography systems.12,13
Vertical uniformity of X-ray beam was an important step to do for the placement of large sized samples and for setting the height of grid.

Figure 5.13. (a) Two lead shields were installed to form a wide slot (slit). (b) The image of slit. The dotted line displays the location of the vertical profile drawn across. (c) The intensity profile vs. distance (mm) shows good uniformity.

Figure 5.14. Intensity was at minimum when the Amptek detector faced one lead shield then rose to maximum in the slot and remains constant until the Amptek detector reaches the other end of the slot, and falling off to minimum when it faced the other lead shield.
To test for uniformity and any beam leakage on either side of lead sheets the using the Amptek detector was scanned close to the slit for distance of 15 mm as shown in Figure 5.14. The scan started from behind one lead shield as detector approached towards the slot the intensity started increasing until a point is reached where only the flat plateau region was observed, the intensity remained constant until the detector face begins to be obscured by the other lead shield.

5.3.6 Anti-Scatter Grid

The grid used in this work had a grid ratio 10:1. The grid acceptance angle, which was expected to be 5.7° from equation (5.3), was confirmed by measuring its transmission. The grid was placed on a rotational stage such that the aligned laser was falling at the center of the grid. This position was marked as the zero degree position for grid and the rotation through any angle was calculated taking the zero degree position as reference. A rotational scan was done using an Amptek detector as shown in Figure 5.16. The intensity is at maximum at the zero degree position and for other angles on either side the intensity starts decreasing. This rotation stage was capable to rotate 3° in both directions clockwise and counter clockwise using ACP software installed on lab computer. If rotational scan could have been done for a bigger angular range, the intensity would have fallen to minimum on either side of the rotation of the grid.
Figure 5.16. shows the grid setting for maximum transmission. The grid could collect scatter up to 6° in either direction.

It also justifies that the center of the grid is at the primary beam axis.

5.4 Coherent Scatter Static Images

Preliminary images were taken with a static, stationary sample, illuminated by the slot beam. In this work, animal fat was used as a phantom for healthy tissue, as fat is a primary component of breast tissue. Carcinoma is known to have a coherent scatter peak at 13° at the Mo Kα line. For that reason polycrystalline graphite, with a diffraction peak of 12.2° was chosen a phantom for carcinoma. Because the peak from graphite is closer in angle to fat which is at 9° at 17.5 keV, it should be harder to detect and therefore be a suitable phantom. Images with the grid tilted from 9° to 18° were obtained. The signal intensity for a particular type of phantom is the maximum at its characteristic angle. The width of the signal for graphite or fat is similar and depends upon the width of slot or aperture used in preliminary measurements.
5.4.1 Diffraction Profiles of Graphite And Fat With An Aperture

Graphite was used as a phantom of the breast cancer tissue as it serves as surrogate for breast carcinoma. In order to verify the diffraction ring from graphite, the wide slot was covered with lead pieces except for a 4 mm aperture. The graphite sample mounted in front of this aperture produced the diffraction ring shown in figure 5.17 (a) and the radial integration in figure 5.17 (b). Peaks were observed at 12° and 20°. When the grid was placed at 12° in front of the image plate, only the expected part of ring passed through the grid, as shown in figure 5.18. An intensity profile versus distance (mm) was drawn across the signal, and the intensity profile for a lane width of 10 pixels was imported to Excel program. The distance was converted to angle as

\[ \theta = \tan^{-1} \frac{x}{D}, \]

where x is the distance from the direct beam to the center of signal on grid as measured in Image Gauge software and D is the measured distance, D = 160 ± 5 mm, from the sample to image plate. Because the peak was slightly shifted from its known angle (due to the known d spacing of graphite), the corrected distance D was calculated from the shifted angle to be D ~ 165 mm. The same procedure was adopted for fat diffraction rings also; the distance was set at 180 mm for coherent scatter peak location at about 9°.
Figure 5.17. (a) shows the graphite diffraction rings, the sample was irradiated through a 4mm diameter aperture with the tube voltage at 46 kV and current at 0.92 mA for an exposure time of 20 minutes. (b) Displays the radial distribution of intensity versus 2θ angle (degrees) obtained from the image using fit 2D software.
Figure 5.18. (a) Part of the graphite diffraction ring is transmitted through the grid tilted at 12°. The width of ring is the same as the diameter of the slot (b) The plot of intensity vs. angle is shown for a horizontal profile through the center of the arc. The width of the peak is ±6° due to the grid acceptance angle. The rapid intensity variation is due to the individual lead strips in the grid.

Fat diffraction rings were produced with a 1 cm thick beef fat phantom. An aperture of 4 mm was used at 9° at distance D = 180 mm. Figure 5.19 (a), (b) and (c) shows the diffraction ring from beef fat phantom, the fit2D software radial integration peak, lastly its intensity vs. angle profile from data imported in Excel program from image gauge software.
Figure 5.19. The beef fat diffraction ring at 9° taken with a 4 mm aperture 4mm, at 46kV and 0.92mA with an exposure time 20 minutes. (b) The radial distribution plot of intensity versus angle θ (degrees). (c) The intensity profile for the diffraction ring; it peaks at 10° rather than 9° which may be due to scatter from water inside fat.
In principle the fat peak should lie at 9° but its location was found to be about 10°, due to additional background from Compton scatter. The Compton scatter follows the grid transmission and so forms a triangular background peaking at the grid tilt angle of 12°. This can be seen for both the graphite and fat profiles in Figures 5.18 and 5.19. Figure (c) is the intensity profile drawn in Image gauge software for lane width of 200, this data is imported in Excel software, whereas figure (b) intensity profile has peak located at 9°, in order to make this happen the distance set between the sample and the detector was ~ 180 mm.

5.4.2. Graphite & Fat Coherent Scatter Images Through 5mm Slit

A slot set to approximately 5 mm in width was used to obtain coherent scatter images for beef fat and graphite samples, using the setup of figure 5.5.

A two part phantom was constructed, with the upper half a 10 mm thick graphite sample and the lower half beef fat of about the same thickness. The coherent signal was collected from the phantom at grid tilt angles of 9° and 12°, as shown in figure 5.20. The image clearly shows the coherent scatter signal from the graphite, a surrogate for breast cancer, is enhanced compared to the normal fat tissue when the grid is tilted to 12°. The sample is 1 cm thick, which is similar to the size of a typical tumor detected by mammography.
Figure 5.20. (a) The geometry of phantom (b) Image from phantom at 9° where fat is dominant (c) Image at 12° shows scatter from graphite is stronger. The phantom was exposed for 20 minutes at 46 kV and 0.92 mA.

The thin vertical lines in the images shown in Figure 5.20 are due to the grid structure.

The reason that the fat signal was still captured on the image plate at 12°, even though its characteristic angle is 9°, was that the grid could collect signal up to ± 6°.

The fat-graphite phantom was imaged for coherent scatter at higher tilt angles 14°, 16°, 18° as shown in Figure 5.21.
At higher angles above 12° it was noticed that the intensity of graphite signal was dominant but decreased in magnitude.

5.5 Contrast Calculations

Contrast for the purpose of comparing images was defined as

$$\text{Contrast} = \frac{I_{\text{Graphite}} - I_{\text{Fat}}}{I_{\text{Graphite}}}$$  \hspace{1cm} (5.5)
where $I_{\text{Graphite}}$ is the intensity of coherent signal from graphite and $I_{\text{Fat}}$ is the intensity of coherent signal from fat. The variation of contrast with tilt angle (degrees) is shown in figure 5.22. The

![Figure 5.22. Variation of contrast with tilt angle. Contrast is negative at 9° because the intensity of fat signal is greater than the intensity of graphite signal. At other tilt angles the contrast is positive and increases at higher tilt angles.](image-url)
Figure 5.23. Schematic of experimental setup with low angle and high angle shields placement. The shields are placed on low angle side and the high angle sides of the wide slot after the sample so that the clean signal could be collected.

In order to improve the contrast low angle and high angle shields were installed. The purpose of the low angle shield was to block the direct beam and the fat signal. The high angle shield served the purpose of blocking the scatter from water in fat at higher angles and also to block Compton scatter at high angles. The schematic is shown in figure 5.23.

A static graphite-fat phantom coherent scatter image at $12 \pm 1^\circ$ is shown in figure 5.24, the low and high angle shields are displayed as black dotted rectangles.

Static images were also taken for the graphite-fat phantom at $9^\circ$ and at $14^\circ$ and higher angles; cropped images in artificial colors are displayed in figure 5.25.
Figure 5.24. (a) Graphite Fat phantom (b) Coherent scatter image of graphite-fat phantom image at $12 \pm 1^\circ$. The low angle and high angle shields are marked as black dotted rectangles.
Intensity profiles were drawn across images in image gauge software for a lane width ~ of 200, from these profiles the data was imported in Excel program and the plots were drawn. From the maximum and minimum values for the graphite and fat profiles the contrast was calculated for all tilt angles in table 1. The contrast calculated for the image at the tilt angle of 9° came out negative since the peak intensity value of fat is greater than that of graphite, as expected at that angle. At higher angles, 14° and 16°, the graphite signal became less intense, at 18° it was barely visible in the image whereas fat started picking up at this angle because of a second diffraction peak.

Figure 5.25  (a) The scatter signal from both parts of phantom at 9°  (c) Scatter signal of phantom at 16°  (d) Coherent scatter signal at 18°. The phantom was exposed for 20min. at 46 kV and 0.92 mA.
Table 1.

<table>
<thead>
<tr>
<th>Profile Intensity</th>
<th>9°</th>
<th>13°</th>
<th>14°</th>
<th>16°</th>
<th>18°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Graphite max</td>
<td>630</td>
<td>1194</td>
<td>4694</td>
<td>1525</td>
<td>1043</td>
</tr>
<tr>
<td>Graphite min</td>
<td>8</td>
<td>2.7</td>
<td>9.1</td>
<td>0.67</td>
<td>0.7</td>
</tr>
<tr>
<td>Fat max</td>
<td>761</td>
<td>974</td>
<td>3069</td>
<td>690</td>
<td>279</td>
</tr>
<tr>
<td>Fat min</td>
<td>10</td>
<td>8.4</td>
<td>20</td>
<td>0.45</td>
<td>0.37</td>
</tr>
<tr>
<td>Graphite Peak</td>
<td>622</td>
<td>1191</td>
<td>4685</td>
<td>1525</td>
<td>1042</td>
</tr>
<tr>
<td>Fat Peak</td>
<td>750</td>
<td>965</td>
<td>3049</td>
<td>689</td>
<td>279</td>
</tr>
<tr>
<td>Signal = Graphite max – Fat max</td>
<td>-130</td>
<td>220</td>
<td>1624</td>
<td>835</td>
<td>763</td>
</tr>
<tr>
<td>Signal/Background = Signal/Fat Peak</td>
<td>-0.17</td>
<td>0.22</td>
<td>0.53</td>
<td>1.21</td>
<td>2.7</td>
</tr>
<tr>
<td>Contrast = Signal/Graphite Peak</td>
<td>-0.20</td>
<td>0.18</td>
<td>0.34</td>
<td>0.55</td>
<td>0.73</td>
</tr>
</tbody>
</table>

These contrast values with the shield in place appear higher than without the shield. However in some cases the fat phantom may have been in a region of low incident intensity, which makes a numerical comparison difficult compare to figure 5.22.

**5.6 Scanned Images**

Scanned imaging was developed to demonstrate larger, more realistic phantoms in the manner of a conventional slot scan system. The experimental setting is shown in figure 5.26.
Figure 5.26. The experimental set-up for scanned images, the red arrows indicate the direction of movement of stage 1 for sample holder and the stage 2 for image plate.

Stage 1 was connected to the sample holder and the arrow indicates the direction of scan. Stage 2 had the image plate. In front of image plate a stage was built to hold the grid stationery. The arrow specifies the direction of scan. When the sample is held in the sample holder it is at the beam axis. The rotation stage is rotated to the desired characteristic angle 2θ for a particular sample. Figure 5.26 displays schematic diagram of experimental set up shown in figure 5.25.
Stage 1 and stage 2 were moved simultaneously in one direction at a speed ratio equal to the magnification factor $M$. The scanned speeds have to be matched to achieve good resolution without blurring. The speed matching was verified by employing the resolution phantom in figure 5.28. The resolution phantom was held in front of the 5mm wide slot with the sample holder. The distance of phantom from the Mo source was 630 mm. The image plate was placed on stage 2. Both stages were connected to the computer and their movement was controlled by ESP300 software. The resolution phantom image was taken with no grid, and with the rotation stage set to zero angle.
Figure 5.28. Scanned image of resolution phantom done at 25 kV and 0.05 mA. The numbers at right describe the period of the line spacings, in line pairs per mm.

The magnification factor $M$ was calculated as

$$ M = \frac{\text{Distance between source and Image Plate}}{\text{Distance between source and Object}} = \frac{630\text{mm}}{440\text{mm}} = 1.4 $$  \hspace{1cm} (5.6)

The speed for the image plate was set to the maximum limit for the 850 B actuator, 0.4 mm/s.

Accordingly the velocity for stage 1 for sample holder was set up

$$ V_{\text{Resolution Phantom}} = \frac{V_{\text{Image Plate}}}{M} = \frac{0.4\text{mm/s}}{1.4} = 0.27\text{ mm/s} $$  \hspace{1cm} (5.7)

The resultant image is shown in figure 5.28. Intensity profiles were drawn in image gauge at several positions on the resolution phantom.
Figure 5.29. Profile through Scanned image of resolution phantom taken at 25 kV and 0.05 mA. The spacing between lines on the phantom is $1/1.5 = 0.67$ mm but the magnification was 1.4, so the spacing between lines is 0.93 mm.

The static image of resolution phantom was also taken, as shown in Figure 5.30. The resolution phantom was held in sample holder such that all five line pairs are exposed. The intensity profile for $lp 1.5/mm$ is also shown for comparison in figure 5.30.

For each profile the average contrast

$$Contrast = \frac{I_{\text{Peak Value}} - I_{\text{Valley Value}}}{I_{\text{Peak Value}}}$$  \hspace{1cm} (5.8)$$

and the peak spacing was calculated and plotted against the line pair /mm ($lp/mm$). The spatial frequency was taken from the label on the resolution phantom. This plot is called Modulated Transfer Function (MTF).
The spacing between lines on the phantom is $\frac{1}{1.5} = 0.67$ mm but the magnification was 1.4, so the spacing between lines is 0.93 mm.

The MTF was drawn for both static and scanned images as displayed in figure 5.29.

MTF plots for static and scanned image show good agreement with each other.

A static and scanned graphite sample was imaged as shown in figure 5.30 (b).

Figure 5.30 (a) static Image of Resolution Phantom taken at 25 kV and 0.05 mA for 2 seconds exposure time; (b) A profile at the position marked at 1.5 lp/mm.

Figure 5.31 MTF plots for both static and scanned images.
The graphite and graphite-fat phantom was scanned as shown in figure 5.32 (a) and (b).

![Figure 5.32. (a) Static image of graphite at 12° taken at 46 kV and 0.92 mA for 20 min. (b) Scanned image of graphite at 12° taken at 46 kV and 0.92 mA for 40 min.](image)

In figure 5.32 (a) the static image of graphite through a 5 mm slot is shown. In this image the holes in the grid stand are clearly seen. Figure 5.32 (b) shows a scanned image of a 50 mm wide graphite sample. Because the grid was stationary, the image of the holes in the stand seems smudged, as expected. The source was turned on 30 minutes before the scanning of sample and image plate was started. When the sample traversed ~ 35 mm, the source was turned off. That was the maximum distance reached by the image plate stage moving at ratio with that of sample stage equals the magnification factor.

A fat-graphite phantom was also scanned at 12° (figure 5.33 (b)), the coherent signal from graphite looks evident.
A checkered sample was also scanned; its schematic is shown in figure 5.35. The two graphite samples, each one an inch in width on the diagonal produced traces of coherent scatter although the beam intensity was clearly not uniform from top to bottom. The size of the signal area roughly corresponds the size of sample exposed to the X-ray beam.
At this point Moly source died. It has been replaced with a new Mo source and co-workers have continued since then. Shielding was improved for repeatable contrast. Good contrast resolution scanned images were obtained which is promising for a diagnostic system.\textsuperscript{14} Laila Hassan,\textsuperscript{14} has developed Monte Carlo MatLab code to simulate an approximate experimental system under the same conditions, for example, tube voltage, filtration, source, distance, grid distance, grid tilt angle and grid ratio. In this model the individual photon tracks were generated and passed on to the detector, binned into pixels. The probabilities were tested for absorption and Compton scatter of photons. The diffraction rings of graphite and fat at characteristic angles were simulated and compared with experimental results.\textsuperscript{16} Results are in good qualitative agreement with the experiment. In conclusion the wide slot system built for static and scanned images was a successful one; and our experiment shows that there is potential to add tissue typing in screening mammography with no increase in dose.
References


Chapter 6  Summary

Diffraction enhanced imaging (DEI) is a technique that detects the angular deflection of X rays from boundaries or edges to enhance contrast in images. The first refractive contrast imaging DEI system in this work was comprised of a conventional polychromatic X ray Cu source, NaI detector, multichannel analyzer (MCA), a multifiber collimating optic A076H9 and two (400) silicon crystals. The transmission of optic was also calculated 29 ± 5% in integrated energy range 4 – 20 keV. Each silicon crystal was stationed on a rotating stage with angular resolution step size 0.05° at about the Bragg angle. Rotational scans were performed to obtain the first diffracted beam. This X-ray beam was monochromatic; when this X-ray beam fell within the acceptance angular range of the second crystal, it was diffracted and finally collected on to the detector. The FWHM of the rocking curve Gaussian was one - tenth as wide as the peak width obtained from the first crystal. The contribution to the rocking curve width from the energy width of the Kα line for angular range was calculated to be 0.3 mrad, which was found in good agreement with the experimental measured value of 0.3 ± 0.2 mrad. The beam intensity was very much reduced after diffraction from the second crystal due to the loss of that part of the beam impinging on the second crystal outside its angular bandwidth.

A step phantom sample was hung between two silicon crystals; the X-ray image was taken and intensity profiles were measured. The data of set of step phantom images was imported into Excel software for analysis; it was normalized, interpolated, and divided by the output optic data, peaks were shifted to match peaks with the beam image with no phantom in it. No fringe effects were observed. The width of the refraction band was expected to be bigger than that of the pixel size, but no edge enhancement was observed because the expected angular deflection was small and also because the beam was highly non - uniform.
A (cylindrical) tube sample was also imaged at the peak position of the second crystal; this sample was imaged at different angular positions on rocking curve. The images taken from peak position to one-third of FWHM did not display any visual refraction contrast at the boundaries.

Data for tubing phantom was also analyzed in Excel, and an intensity plot versus distance was drawn, interpolating tubing data was divided by output optic data, but again no edge enhancement could be seen.

The lack of observable edge enhancement may have been due to the optic structure which obscured refraction effects.

Therefore it was decided to work with the monolithic optic 3369 which would give a more uniform output. In addition a new set of (220) crystals, which should give a smaller rocking curve width were employed. Similar steps were followed for system optimization and alignment of DEI system as before. In this case the expected angular width from diffraction of second crystal is slightly bigger than expected. The efficiency of the second crystal was calculated by taking into account voltage, current, and the number of counts at the peak positions of scans for both silicon crystals. The efficiency of the second crystal was ± 0.0028, which was in good agreement with the ± 0.0025 estimated from images. When the system was ready the step phantom and tubing samples were imaged at the peak position of the second crystal. For each image the data was imported, normalized and interpolated. This interpolated data was divided by the optic output data with no phantom. Finally the intensity versus distance plot was drawn for both samples. No refraction effect at edges was observed.

Better results could be achieved if a higher resolution detector or phantom of bigger step size and larger diameter thin walled tubing would be used.
A coherent scatter experiment was discussed in chapter 5. A slot scan mammography system was built to distinguish the coherent scatter of the breast cancer tissue from that of the normal fatty breast tissue since the characteristic angle $2\theta$ of Bragg diffraction of a diseased breast tissue is different from that of a normal breast tissue. This $2\theta$ angular dependence of the coherent scatter cross section is detectable at low angles. At high angle the Compton scatter obscures the information. In our experiment a simple 10:1 focused grid was used for angular selectivity. The grid was capable of collecting scatter up to $6^\circ$ from the peak transmission. The grid was placed at the characteristic angle so that instead of collecting the entire diffraction cone from each volume element, only the portion from one side was transmitted onto the image plate. The final image from a rectangular slice appeared as a vertical band.

The coherent scatter system employed a molybdenum (Mo) source placed on stages that had five degrees of freedom: parallel to the rail (z axis), horizontal (x), vertical (y) and rotation about the vertical axis. The Mo source was aligned using four washers ranging from 5 cm from the source for the first washer to 115 cm for the fourth washer. Horizontal and vertical profiles were drawn across images of the beam through the center of the washers to verify uniformity of the beam. In order to create a $5 \text{ mm} \sim$ wide slot, two lead shields were installed. An Amptek detector was used to check for leakage of the X-ray beam and its uniformity across the slot. It showed good uniformity. Two rails were installed. On one rail the stage for the sample holder was affixed in such a way that the sample holder was extended beyond the wide slot and it was placed above the rotation stage which rotated the second rail. The second rail was fixed to the rotation stage to hold the image plate. In this work, animal fat was used as a phantom for healthy tissue, as fat is a primary component of breast tissue. Carcinoma is known to have a coherent scatter peak at $13^\circ$ at the Mo K$_\alpha$ line. For that reason graphite, with a diffraction peak of $12.2^\circ$ was chosen a
phantom for carcinoma. Because the peak from graphite is closer in angle to fat, which is at 9° at 17.5 keV, graphite should be harder to detect the carcinoma and therefore be a suitable phantom. Before placing the grid and slot in the system, diffraction rings were obtained for graphite and fat samples using a circular aperture ~ 5 mm in diameter. Intensity profiles were drawn across the images. Using image gauge software and the data was imported in Excel. The peaks were found to be about 12° and 9° respectively, for graphite and fat. Fit 2D software was used to do the radial integration for the diffraction rings of both samples. Again, the peaks were located at about 9° and 12°. For static images a two part phantom was constructed, with the upper half a 10 mm thick graphite sample and the lower half beef fat of about the same thickness. The coherent signal was collected from the phantom at grid tilt angles of 9°, 12°, 14° and 16°. Coherent scatter signal was dominant at 9° and graphite at 12°. At higher angles the signal from graphite was much reduced but still dominant over fat as the anti - scatter grid could collect the signal up to ± 6°. The contrast was calculated for each image and plotted versus tilt angle. Using the definition of contrast as the normalized graphite to fat difference, contrast for 9° image was negative since the signal from fat was dominant, and for the other images the contrast was positive, and at 18° it was a maximum.

The slot scan mammography system was also meant to do scanned images; for this purpose the second stage for image plate and the stage one for the sample holder were moved separately at different speeds controlled through computer software. The ratio of speeds was the calculated magnification factor, M. A static and a scanned image of a resolution phantom were taken. Intensity profiles for each lp/mm were drawn and the contrast was calculated for each profile. Finally the average contrast versus lp/mm, i.e. an MTF plot for static and scanned images showed good agreement. This showed that the scanning speeds were in the correct ratios. Some
scanned coherent scatter images were collected before the Mo source failed. The dead source was replaced with the new Mo source and co-workers took over.

The shielding and system were refined to achieve repeatable contrast, which was also in good agreement with the simulation. Good contrast resolution scanned images were obtained which is promising for a diagnostic system.