ABSTRACT

WANG, XIAOQIN. Line X-Ray Source for Diffraction Enhanced Imaging in Clinical and Industrial Applications. (Under the direction of Mohamed A. Bourham.)

Mammography is one type of imaging modalities that uses a low-dose x-ray or other radiation sources for examination of breasts. It plays a central role in early detection of breast cancers. The material similarity of tumor-cell and health cell, breast implants surgery and other factors, make the breast cancers hard to visualize and detect.

Diffraction enhanced imaging (DEI), first proposed and investigated by D. Chapman is a new x-ray radiographic imaging modality using monochromatic x-rays from a synchrotron source, which produced images of thick absorbing objects that are almost completely free of scatter. It shows dramatically improved contrast over standard imaging when applied to the same phantom. The contrast is based not only on attenuation but also on the refraction and diffraction properties of the sample. This imaging method may improve image quality of mammography, other medical applications, industrial radiography for non-destructive testing and x-ray computed tomography. However, the size, and cost, of a synchrotron source limits the application of the new modality to be applicable at clinical levels.

This research investigates the feasibility of a designed line x-ray source to produce intensity compatible to synchrotron sources. It is composed of a 2-cm in length tungsten filament, installed on a carbon steel filament cup (backing plate), as the cathode and a stationary oxygen-free copper anode with molybdenum coating on the front surface serves as the target. Characteristic properties of the line x-ray source were computationally
studied and the prototype was experimentally investigated. SIMION code was used to computationally study the electron trajectories emanating from the filament towards the molybdenum target. A Faraday cup on the prototype device, proof-of-principle, was used to measure the distribution of electrons on the target, which compares favorably to computational results. The intensities of characteristic x-ray for molybdenum, tungsten and rhodium targets were investigated with different window materials for -30kV to -100kV applied potential. Heat loading and thermal management of the target has been investigated computationally using COMSOL code package, and experimental measurements of target temperature rise was taken via thermocouples attached to the target. Temperature measurements for low voltage, low current regime without active cooling, were compared to computational results for code-experiment benchmarking. Two different phantoms were used in the simulation of DEI images, which showed that the designed x-ray source with DEI setup could produce images with significant improved contrast.

The computational results, along with experimental measurements on the prototype setup, indicate the possibility of scale up to larger area x-ray source adequate for DEI applications.
LINE X-RAY SOURCE FOR DIFFRACTION ENHANCED IMAGING

IN CLINICAL AND INDUSTRIAL APPLICATIONS

by

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Xiaoqin Wang was born on January 7th, 1977 in Ling Chuan County, Shanxi Province, China. Her high school studies inspired her strong interest in physics, chemistry, and geography. Geography was her primary interest until her admission to the department of nuclear materials and technology in Chengdu University of Technology (CDUT) in 1994. CDUT presented many opportunities in the applications of radiation detection technologies. After completing her bachelor degree in 1998, she was admitted to the graduate school in CDUT in the same program. She worked for 3 years with Dr. Wenyi Jia, who is a distinguished professor in radiation, X-ray, γ-ray and neutron activation detection. In August 2002, she joined North Carolina State University as a Ph.D. candidate in the Department of Nuclear Engineering. Since 2003, she is working on the line-filament X-ray source for DEI applications as her Ph.D. research project, and greatly enjoyed this interesting research.

North Carolina State University provided her with a broad view of nuclear engineering and good cultural atmosphere. Also, NC State provides a lot of sports activities; she just learned swimming, golf, tennis and yoga, which she never tried before. In 2005, as a teaching assistant in a thermal hydraulic class, the opportunity attracted her interest in thermal hydraulic safety analysis of nuclear power plant. She is going to join AREVA as a safety analysis engineer after completion of her dissertation in August 2006.
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# Table of Contents

LIST OF FIGURES ........................................................................................................................................ vi

LIST OF TABLES ........................................................................................................................................... xii

1 INTRODUCTION ........................................................................................................................................ 1

2 THEORY .................................................................................................................................................... 7

2.1 ELECTRON GENERATION ....................................................................................................................... 7

2.2 ELECTRON TRAJECTORIES ................................................................................................................... 9

2.3 X-RAY GENERATION AND INTERACTIONS WITH MATTERS ............................................................. 12

2.3.1 X-ray generation .................................................................................................................................. 12

2.3.2 X-ray interactions with matters ....................................................................................................... 14

2.4 X-RAY IMAGING .................................................................................................................................... 17

2.4.1 Conventional x-ray imaging .............................................................................................................. 17

2.4.2 Diffraction Enhanced Imaging (DEI) .................................................................................................. 20

2.5 HEAT TRANSFER ................................................................................................................................... 33

2.5.1 Heat Production .................................................................................................................................. 33

2.5.2 Heat Transfer ..................................................................................................................................... 34

2.6 DOSE EVALUATION ............................................................................................................................... 36

3 COMPUTATIONAL SIMULATION .............................................................................................................. 40

3.1 DESIGN OF LINE X-RAY SOURCE GENERATOR .................................................................................. 40

3.2 SIMULATION OF ELECTRON TRAJECTORIES .................................................................................... 43

3.2.1 Calculation of Thermionic Electron Current Density ................................................................. 43

3.2.2 Electron Trajectories ....................................................................................................................... 47

3.3 SIMULATION OF X-RAY WINDOW OPTIONS ..................................................................................... 54

3.4 SIMULATION OF TARGET HEAT LOADING ......................................................................................... 66
3.5 SIMULATION OF DEI IMAGING ............................................................................................................ 75
3.6 SIMULATION OF ABSORBED DOSE ....................................................................................................... 81

4 LAB-BASED EXPERIMENTS ................................................................................................................... 83
  4.1 EXPERIMENTAL SETUP ........................................................................................................................ 83
  4.2 MEASUREMENT OF ELECTRON DISTRIBUTION ON THE TARGET .................................................... 85
    4.2.1 Experimental setup for electron distribution measurements .................................................... 85
  4.3 EXPERIMENTAL MEASUREMENTS OF TARGET TEMPERATURE RISE ............................................. 90

5 CONCLUSIONS AND RECOMMENDATIONS ....................................................................................... 94
  5.1 CONCLUSIONS ................................................................................................................................... 94
  5.2 RECOMMENDATIONS .......................................................................................................................... 95

6 LIST OF REFERENCES ............................................................................................................................. 97

7 APPENDICES .......................................................................................................................................... 101
  APPENDIX A SIMION7.0 CODE GEOMETRY INPUT PROGRAM .......................................................... 102
  APPENDIX B MCNP CODE INPUT FILES ............................................................................................. 105
  APPENDIX C X-RAY SPECTRUM ............................................................................................................ 110
  APPENDIX D ESTIMATION OF OPERATION TIME ............................................................................. 130
List of Figures

FIGURE 2-1 ELECTRON TRAJECTORIES DISTRIBUTION WITH UNBIASED AND BIASED FOCUSING CUP (FROM DENDY P.P. 1999) ........................................................................................................................................12
FIGURE 2-2 PRODUCTION OF BREMSSTRAHLUNG X-RAY .......................................................................................................................... 13
FIGURE 2-3 PRODUCTION OF CHARACTERISTIC X-RAY ............................................................................................................................ 13
FIGURE 2-4 TYPICAL CONTINUOUS X-RAY SPECTRUM ........................................................................................................................... 14
FIGURE 2-5 PHOTOOELECTRIC CROSS-SECTION OF CALCIUM AS A FUNCTION OF X-RAY ENERGY .......... 17
FIGURE 2-6 LINEAR ATTENUATION COEFFICIENTS FOR BREAST TISSUES AND TISSUE-EQUIVALENT MATERIALS (FROM TAIBI, 2003) .......................................................................................................................... 19
FIGURE 2-7 CONVENTIONAL X-RAY TUBE SPECTRUM ..................................................................................................................... 19
FIGURE 2-8 REFRACTION OF THE X-RAY BEAM AT A BOUNDARY BETWEEN MEDIA WITH REFRACTIVE INDICES N1 AND N2: (A) FLAT BOUNDARY; (B) CURVILINEAR BOUNDARY. (FROM V. N. INGAL, 1998) .......... 21
FIGURE 2-9 A DEI BRAGG SETUP AND A RADIOGRAPHY SETUP (FROM D. CHAPMAN. 1997) ......................... 22
FIGURE 2-10 REFLECTIVITY CURVES FROM A PERFECT SI CRYSTAL IN THE SYMMETRICAL BRAG CASE (FROM R. SUORTTI, 2004) ........................................................................................................................................ 23
FIGURE 2-11 THE ROCKING CURVE AND EXAMPLE OF THE LOWER AND HIGHER SIDE IMAGES [31] ............... 26
FIGURE 2-12 MONOCHROMATIC BEAM FLUX IN THE NSLS X15A HUTCH USING SILICON [1 1 1], [3 3 3], [4 4 4] AND [5 5 5] CRYSTAL-DIFFRACTION PLANES (REF.: Z. ZHONG 2000) ..................................................... 30
FIGURE 2-13 SCHEMATIC DIAGRAM OF ANODE WITH CENTRAL COOLING CHANNEL ................................................... 35
FIGURE 2-14 PHOTON FLUX-TO-DOSE RATE CONVERSION FACTORS [REF: ICRP-21] ................................................. 39
FIGURE 2-15 PHOTON FLUX-TO-DOSE RATE CONVERSION FACTORS IN LOW ENERGY RANGE [REF: ICRP-21]. 39
FIGURE 3-1 SCHEMATIC DIAGRAM OF THE PRINCIPLE-PROOF EXPERIMENTAL SETUP ........................................ 41
FIGURE 3-2 FILAMENT CUP ASSEMBLY (UNITS: CM) ........................................................................................................................ 42
FIGURE 3-3 MOLYBDENUM TARGET CONFIGURATION (UNITS: CM) ...................................................................................... 43
FIGURE 3-4 ELECTRON BEAM CURRENT VERSUS PHOTON FLUX FOR A MO TARGET AT –60kV ......................... 46
FIGURE 3-5  SCHEMATIC OF THE FILAMENT AND TARGET POSITIONS IN THE PROOF-OF-PRINCIPLE EXPERIMENT, THE MAXIMUM ALLOWABLE TILT ANGLE IS $\theta = 22.5^\circ$ IN THIS GEOMETRY ...............................................................47

FIGURE 3-6  TRAJECTORY OF ELECTRONS WITH TARGET AT 0° TILT ANGLE .................................................................49

FIGURE 3-7  TRAJECTORY OF ELECTRONS WITH TARGET AT 15° TILT ANGLE .............................................................49

FIGURE 3-8  TRAJECTORY OF ELECTRONS WITH TARGET AT 22° TILT ANGLE .............................................................49

FIGURE 3-9  ELECTRON DISTRIBUTION ON THE TARGET FOR A 0° TILT ANGLE AT -30kV POTENTIAL ..................50

FIGURE 3-10 ELECTRON DISTRIBUTION ON THE TARGET FOR A 0° TILT ANGLE AT -60kV POTENTIAL ............50

FIGURE 3-11 ELECTRON DISTRIBUTION ON THE TARGET FOR A 15° TILT ANGLE AT -30kV POTENTIAL .......51

FIGURE 3-12 ELECTRON DISTRIBUTION ON THE TARGET FOR A 15° TILT ANGLE AT -60kV POTENTIAL .......51

FIGURE 3-13 ELECTRON DISTRIBUTION ON THE TARGET FOR A 22° TILT ANGLE AT -30kV POTENTIAL .......52

FIGURE 3-14 ELECTRON DISTRIBUTION ON THE TARGET FOR A 22° TILT ANGLE AT -60kV POTENTIAL .......52

FIGURE 3-15  RELATIVE ELECTRON FREQUENCY ALONG Y-AXIS ................................................................................53

FIGURE 3-16  RELATIVE ELECTRON FREQUENCY ALONG X-AXIS ................................................................................54

FIGURE 3-17  DIAGRAM OF THE MCNP WINDOW SIMULATION GEOMETRY ........................................................55

FIGURE 3-18  INTENSITY OF CHARACTERISTIC X-RAY WITH 0.3A ELECTRON BEAM ........................................58

FIGURE 3-19  INTENSITY OF CHARACTERISTIC X-RAY WITH 3A ELECTRON BEAM ........................................58

FIGURE 3-20  SPECTRUM COMPARISON OF 0.001MM THICK LAYER OF VARIOUS METAL FILMS ON GLASS
WINDOW TO GLASS-ONLY WINDOW, ACCELERATING POTENTIAL IS –30kV ........................................................59

FIGURE 3-21  SPECTRUM COMPARISON OF 0.01MM THICK LAYER OF VARIOUS METAL FILMS ON GLASS WINDOW TO GLASS-ONLY WINDOW, ACCELERATING POTENTIAL IS –30kV ..................................................60

FIGURE 3-22  X-RAY SPECTRUM WITH Mo TARGET, 0.001MM RH + GLASS WINDOW, -30kV .........................61

FIGURE 3-23  X-RAY SPECTRUM WITH Mo TARGET, 0.01MM RH + GLASS WINDOW, -30kV .........................61

FIGURE 3-24  X-RAY SPECTRUM WITH Mo TARGET, 0.001MM Mo + GLASS WINDOW, -30kV .......................62

FIGURE 3-25  X-RAY SPECTRUM WITH Mo TARGET, 0.01MM Mo + GLASS WINDOW, -30kV .......................62

FIGURE 3-26  X-RAY SPECTRUM WITH Mo TARGET, 0.001MM Al + GLASS WINDOW, -30kV .......................63

FIGURE 3-27  X-RAY SPECTRUM WITH Mo TARGET, 0.01MM Al + GLASS WINDOW, -30kV .......................63

FIGURE 3-28  X-RAY SPECTRUM WITH Mo TARGET, 0.001MM Be + GLASS WINDOW, -30kV .......................64
FIGURE 3-29 X-RAY SPECTRUM WITH Mo TARGET, 0.01MM Be +GLASS WINDOW, -30kV .............................64
FIGURE 3-30 X-RAY SPECTRUM WITH Mo TARGET, GLASS WINDOW, -30kV ..................................................65
FIGURE 3-31 X-RAY SPECTRUM WITH Mo TARGET, GRAPHITE WINDOW, -30kV .............................................65
FIGURE 3-32 TEMPERATURE DISTRIBUTION ON THE TARGET AFTER 1800S, 3MA BEAM CURRENT, AND -3KV
ACCELERATING VOLTAGE ......................................................................................................................67
FIGURE 3-33 TEMPERATURE DISTRIBUTION ON THE TARGET AFTER 1800S, 3MA BEAM CURRENT, AND -30kV
HIGH VOLTAGE.......................................................................................................................................68
FIGURE 3-34 TEMPERATURE DISTRIBUTION ON THE TARGET AFTER 1800S, 3MA BEAM CURRENT, AND -60kV
HIGH VOLTAGE.......................................................................................................................................68
FIGURE 3-35 TEMPERATURE DISTRIBUTION ON THE TARGET AFTER 1800S, 3.0A BEAM CURRENT, AND -3KV
HIGH VOLTAGE WITH LIQUID NITROGEN ACTIVE COOLING ......................................................................70
FIGURE 3-36 TEMPERATURE DISTRIBUTION ON THE TARGET AFTER 1800S, 3.0A BEAM CURRENT, ..........71
FIGURE 3-37 TEMPERATURE DISTRIBUTION ON THE TARGET AFTER 90S, 3.0A BEAM CURRENT, .................72
FIGURE 3-38 TEMPERATURE DISTRIBUTION ON THE ALUMINUM TARGET AFTER 1800S, 3MA BEAM CURRENT,
AND -1.25KV HIGH VOLTAGE...................................................................................................................74
FIGURE 3-39 TEMPERATURE DISTRIBUTION ON THE ALUMINUM TARGET AFTER 1800S, 3MA BEAM CURRENT,
AND -1.5KV HIGH VOLTAGE....................................................................................................................74
FIGURE 3-40 TEMPERATURE DISTRIBUTION ON THE ALUMINUM TARGET AFTER 1800S, 3MA BEAM CURRENT,
AND -2.5KV HIGH VOLTAGE....................................................................................................................75
FIGURE 3-41 ROCKING CURVES OF Si (1 1 1) AND Si (3 3 3 ) AT 17.489KEV....................................................76
FIGURE 3-42 X-RAY ENERGY VERSUS REFLECTIVITY OF Si (1 1 1) .................................................................77
FIGURE 3-43 SCHEMATIC OF PHANTOM ..........................................................................................................78
FIGURE 3-44 DEI IMAGES (A) LOW ANGLE SIDE, (B) HIGH ANGLE SIDE (C) REFRACTION ANGLE IMAGE (DEI)
(d) THE APPARENT ABSORPTION IMAGE..................................................................................................79
FIGURE 3-45 SCHEMATIC OF PHANTOM ..........................................................................................................80
FIGURE 3-46 DEI IMAGES (A) LOW ANGLE SIDE, (B) HIGH ANGLE SIDE (C) REFRACTION ANGLE IMAGE (DEI)
(d) THE APPARENT ABSORPTION IMAGE..................................................................................................81
FIGURE 7-37 X-RAY SPECTRUM WITH W TARGET, GRAPHITE WINDOW, -100kV ........................................... 127
FIGURE 7-38 X-RAY SPECTRUM WITH W TARGET, 0.01MM RH +GLASS WINDOW, -100kV .............................. 128
FIGURE 7-39 X-RAY SPECTRUM WITH W TARGET, 0.01MM MO +GLASS WINDOW, -100kV .............................. 128
FIGURE 7-40 X-RAY SPECTRUM WITH W TARGET, 0.01MM AL + GLASS WINDOW, -100kV ......................... 129
FIGURE 7-41 X-RAY SPECTRUM WITH W TARGET, 0.01MM BE + GLASS WINDOW, -100kV ......................... 129
List of Tables

TABLE 1-1 CLINICAL IMAGING AND THERAPEUTIC TECHNOLOGIES (FROM P SUORTTI, 2003)......................... 1

TABLE 3-1 FILAMENT TEMPERATURE VERSUS ELECTRON FLUX AT -30kV .................................................. 45

TABLE 3-2 FILAMENT TEMPERATURE VERSUS ELECTRON FLUX AT -60kV ................................................ 46

TABLE 3-3 CHARACTERISTIC X-RAY OF TARGET MATERIALS (KEV) ................................................................. 56

TABLE 3-4 INTENSITY OF CHARACTERISTIC X-RAY FOR A 0.3A ELECTRON BEAM FOR DIFFERENT TARGET MATERIALS AND DIFFERENT WINDOW OPTIONS .............................................................. 57

TABLE 3-5 INTENSITY OF CHARACTERISTIC X-RAY FOR A 3.0A ELECTRON BEAM FOR DIFFERENT TARGET MATERIALS AND DIFFERENT WINDOW OPTIONS .............................................................. 57

TABLE 3-6 AVERAGE HEAT FLUX ON THE TARGET ...................................................................................... 66

TABLE 3-7 TEMPERATURE OF THE COPPER TARGET FOR 3MA CASE ........................................................... 69

TABLE 3-8 TEMPERATURE OF THE COPPER TARGET FOR 3.0A CASE ........................................................... 72

TABLE 3-9 AVERAGE HEAT SOURCE INPUT FOR BENCHMARK CASES .......................................................... 73

TABLE 3-10 TEMPERATURE OF THE ALUMINUM TARGET AFTER 1800S ....................................................... 75

TABLE 4-1 FARADAY CUP OUTPUT VOLTAGE (MV) ......................................................................................... 88
1 Introduction

The use of x-rays for medical purposes started almost immediately after Wilhelm Conrad Röntgen’s discovery of x-rays in 1895. The news of the first radiograph of Mrs. Röntgen’s hand spread by press in all developed countries, and the first clinical x-ray images were taken in 1896. Since then the use of x-rays has been the most important diagnostic imaging method. The objectives of biomedical research with different forms of radiations are to understand the basic physics, biochemistry of biological systems, diagnosing disease, and screening population for diseases. There are a variety of methods and before discussing the new designed x-ray source, it is useful to have an overview of the current clinical technologies. They are listed in Table 1-1 with their principal fields of application.

<table>
<thead>
<tr>
<th>Table 1-1 Clinical imaging and therapeutic technologies From P Suortti, 2003</th>
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</thead>
<tbody>
<tr>
<td><strong>Radiography</strong></td>
</tr>
<tr>
<td><strong>CAT scans</strong></td>
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<tr>
<td><strong>Scattering</strong></td>
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<tr>
<td><strong>Nuclear medicine</strong></td>
</tr>
<tr>
<td><strong>Radiotherapy</strong></td>
</tr>
<tr>
<td><strong>Magnetic resonance imaging(MRI)</strong></td>
</tr>
<tr>
<td><strong>Ultrasound</strong></td>
</tr>
<tr>
<td><strong>Infrared</strong></td>
</tr>
<tr>
<td><strong>Neuromagnetism</strong></td>
</tr>
</tbody>
</table>
The scale length extends from whole-body imaging to structures on the atomic and molecular level. Referring to physiological effects, radiation can be termed ionizing or non-ionizing. The dose of ionizing radiation puts limits on imaging methods, but on the other hand, makes radiotherapy possible.

Among those clinical radiation methods, the early detection of breast cancer has been gaining a great deal of attention in recent years. In 2002 approximately 203,500 American women would have been diagnosed with invasive breast cancer. The incidence rate had been increasing at about 4.5% per year in the 1980s, but the rate of increase has slowed. Additionally, there were 54,000 cases of in situ breast cancer (of these, approximately 88% were ductal carcinoma in situ (DCIS). Approximately 39,600 women were dead of breast cancer in 2002, second only to lung cancer in the number of deaths caused among women, and it is the leading cause of death among women between the ages of 40 and 55. It is also the most common non-skin related malignancy among American women (American Cancer Society). However, the situation is not all bad. Breast cancer mortality has been on the decline in recent years, largely due to early detection. The National Breast Cancer Foundation (NBCF) has stated that there has been a 2% annual decrease in breast cancer deaths over the past decade. Ongoing research may result in a cure for or a method to, prevent breast cancer but till then it is widely believed that early detection is the best hope to fighting this disease.\textsuperscript{[2,3]}

The basic principles of X-ray image formation and interpretation in radiography have remained essentially unchanged. The conventional approach relies on X-ray absorption. It works well in distinguishing between hard and soft tissue, like calcium in
bones have a much higher attenuation coefficients. However, in many clinical situations, such as mammography (i.e. detection of breast cancer), there is a need to distinguish between different kinds of soft tissue, between tumors and normal tissue, for instance. According to radiologist Etta Pisano\cite{4}, mammography currently has a very high rate of false positives and false negatives. In a population of undiagnosed women advised by their doctors to have regular diagnostic screening, only five women out of 1000 will actually have breast cancer. But for that same population, the rate of positive mammograms will be 10%, the ratio of false positives to true positives is nearly 20:1. And for about 10-20% of women who have palpable abnormalities, the mammograms won’t show anything. There is thus a driving need to improve breast cancer detection technology.\cite{5,6}

The conventional X-ray imaging approach relies on X-ray absorption and ignores phase information. Phase-sensitive techniques offer ways to complement standard absorption contrast by application of phase information. There are several research groups, which are doing research to combine phase information to improve image contrast. According to Stephen Wilkins who is a member of Australia’s Commonwealth Scientific and Industrial Research Organization (CSIRO), those approaches could be put into three main categories: interferometry, diffractometry and in-line holography. From basic physics point of view, those three approaches may be associated with directly measuring $\varphi$, $\nabla \varphi$ and $\nabla^2 \varphi$ respectively. Ulrich Bones and Michael Hart pioneered X-ray interferometry methods in 1965. In recent years, this technique has been refined for application in clinical medical settings.\cite{7,8,9} By using synchrotron radiation, it shows that
the order of $10^{-9}$ g/cm$^3$ density variations can be detected. However, because of its extreme sensitivity, almost perfect crystal alignment and stability are required for the X-ray interferometer. The technique limits the potential field of view to about 3 cm $\times$ 3 cm. Clinical applications of mammography require a 10 cm $\times$ 10 cm field of view. The second approach first explored at the X-Ray Laboratory in St. Petersburg, Russia, by V.N. Ingal 1995$^{[10]}$ and at CSIRO by Wilkins. The US collaboration to apply diffraction-enhanced imaging (DEI) has been led by D. Chapman (Illinois Institute of Technology), W. Thomlinson (European Synchrotron Radiation Facility in Grenoble, France) and Z. Zhong (Brookhaven National Laboratory)$^{[11]}$. DEI requires an intense monochromatic X-ray beam for reasonable exposure time. DEI images, using synchrotron source, have shown dramatically improved contrast over standard images$^{[12,13,14]}$. If just a detector but no analyzer crystal is in the beam path, the X-rays emerging from the sample at their various angles will propagate through free space until reaching the detector, which is the third approach (A. Snigirev 1995 and S. W. Wilkins 1996)$^{[15,16]}$

Phase-sensitive imaging techniques are showing promising application in industry and clinics$^{[17,18]}$. This system is completely free of scattering and the beam contains only the contribution from x-rays that are affected by absorption, extinction or refraction through a very small angular deflection of the order of micro radians ($5.73 \times 10^{-5}$ degree/micro radian). This arrangement made it possible to obtain higher contrast images from the same object. However, none of these techniques is yet at the clinical stage. For the approaches currently relying on synchrotron radiation, efforts are being made to develop a laboratory-sized source that can provide the needed intensity at the appropriate
energy within acceptable exposure time. V.N. Ingal and Beliaevskaya have continued to explore the use of commercial X-ray tubes (V.N. Ingal 1998)\textsuperscript{19}. Z. Zhong and D. Chapman have carried out similar effort by investigating the application of rotating-anode X-ray source in DEI (Z. Zhong 1997)\textsuperscript{20}. As part of the effort to make the DEI techniques being suitable for clinical radiography, in this study, a designed line X-ray source has been investigated as a possible substitution of synchrotron radiation source.

The core component of this study is the design of the line X-ray generator and its assembly. The source has a 2 cm long tungsten filament installed inside a filament cup made of steel and negatively biased to work as the cathode. The x-ray target is a 3.5 cm diameter and 6.0 cm in length oxygen-free copper cylinder with the front surface coated with a thin layer of molybdenum. The target is at ground potential working as the anode. The filament-target assembly is installed inside a six-inch, six-way vacuum cross. For this proof-of-principle study, the characteristic parameters of the designed X-ray source have been computationally and experimentally investigated. Electron trajectories were obtained from simulation using the SIMION software package. Electron trajectories can be varied, focused and adjusted by varying the biasing voltage on the filament cup (backing plate). Each electron landing on the target corresponds to an x-ray generation spot. The profile of x-ray generation and intensity distribution from the target is obtained from recoding the frequency of electrons landing at each point on the anode. The x-ray window is a glass-viewing vacuum one with a layer of absorber, such as aluminum, molybdenum, beryllium, etc., which may be prepared by sputter deposition techniques to put a thin layer of the absorber on the inside of the window. This glass window partially filters low-energy
bremsstrahlung but keeps the $K_a$ characteristic X-ray passing through. Several window options, absorber materials, were computationally studied. Simulation of images, with and without DEI algorithm, was computationally simulated using MCNP code to investigate the quality and contrast of obtained images. The DEI obtained images show significant improvement over non-DEI images. The dose equivalent surrounding the X-ray generator (outside of the vacuum chamber) has been computationally evaluated and it is far below the permissible dose limits set by NRC, 100mrem/yr, for general public. Computational simulations accomplished by using MCNP code are via a license by Los Alamos National Laboratory to the Department of Nuclear Engineering, North Carolina State University. The heat loading of the anode was accomplished by using the COMSOL heat transfer module, licensed to the author, from which 3-D time-dependent temperature distributions on the target was obtained, with and without active cooling, under various operating conditions.

Experiments on the prototype (proof-of-principle) setup were conducted to measure the electron and temperature distributions on the target. A Faraday cup was used to measure the electron distribution along the length of the line filament. Three thermocouples were attached to the target to obtain the temperature distribution at various biasing potentials. Although these measurements were conducted at low potential, up to 5 kV, which will not generate x-rays, but such measurements provide comparison with computational results and thus validate scalability to higher operating potentials, and higher beam currents.
2 Theory

In this study the concept of area x-ray beam generated by a long line filament, then monochromatized via special crystals and diffracted by a crystal analyzer is investigated. The electron generation is by thermionic emission, similar to conventional x-ray tubes, except that the filament is much longer and thus a rectangular beam could be generated. A major concept in this research is the use of thin layer molybdenum on top of an oxygen-free copper target for better thermal management. Additionally, the concept of absorber thin layer sputter-deposited on a glass window allows for best optimization of the x-ray filtering window without serious vacuum consideration if using a thin beryllium or aluminum window that cannot survive the high vacuum inside the x-ray chamber. This window concept filters part or all the bremsstrahlung, which should be filtered out before directing the characteristic x-ray $K_{\alpha 1}$ towards the crystal monochromators. Collimated x-ray is then directed towards the phantom and the image is recorded on an imaging plate. The images are computationally obtained using MCNP code.

This chapter provides a review of electron generation by thermionic emission, the motion of electrons in electric field, generation of x-ray, interaction of x-ray with matter, theory of diffraction enhanced imaging (DEI), radiation dose equivalent and x-ray target thermal loading.

2.1 Electron Generation

In any metal, there is one or more electron per atom that is free to move from atom to atom. When an electron gains enough energy, it exits the metal. The minimum amount
of energy needed for an electron to exit the metal is called the metal work function and varies from metal to metal. The number of electrons exiting the surface of the metal is a function of the metals’ surface temperature; it is the well-known Richardson-Dushman Law for thermionic emission.

\[ J = AT^2 e^{\frac{W}{kT}} \]  

(2-1)

Where \( T \) is the metal surface temperature in °K, \( W \) is the work function of the metal, \( k \) is the Boltzmann constant, given by \( k = 8.617339 \times 10^{-5} \frac{eV}{K} \) and \( A \) is Richardson’s constant, given by \( A = 1.20173 \times 10^6 \frac{A}{m^2 K^2} \).

Schottky effect determines the electron current density emitted by thermionic emission under vacuum conditions. It introduces the correction for the effect of lowering the work function under vacuum conditions as a result of the image forces and by the electric field at the emitting cathode. The corrected enhancement function is given by the field-enhanced thermionic emission (FEE) equation:

\[ J = AT^2 e^{\left(\frac{W - \Delta W}{kT}\right)} \]  

(2-2)

\[ \Delta W = \left[\frac{eE_c}{4\pi\varepsilon_0}\right]^{1/2} \]

Where \( E_c \) is the electric field strength at the cathode and \( \varepsilon_0 \) is the permittivity of free space, or vacuum. For electric field strengths lower that about \( 10^8 \frac{V}{m} \), the Schottky
equation is accurate. For higher electric field strengths, the use of the Murphy and Good equation for thermo-field (T-F) emission is more appropriate \[^{[21]}\].

2.2 Electron Trajectories

When negative high voltage potential is applied near a hot metal filament, electrons generated by thermionic emission will be pushed away from the surface of the hot filament and follow the electric field direction. The acceleration and spatial distribution of the electrons flying towards the target (anode) affect the intensity distribution of the generated x-ray, and influences the target heat loading. Hence, it is important to determine the electron trajectories of the filament-target assembly under different applied potentials and different focusing cup biasing.

Charged particle optics utilizes the motion of charged particles under the influence of electric, or magnetic fields, or a combination of both. The equation of motion for a charged particle accelerated by a uniform electric field is

\[
a = \frac{F}{M} \rightarrow \frac{dv}{dt} = -\frac{eE}{m}
\]  

(2-3)

Where, \(a\) is the acceleration, \(v\) is the velocity of the particle, and \(m\) is the mass of the charged particle. The electric field could be substituted for by the negative gradient of the potential, and thus for an electron:

\[
m_e \frac{dv}{dt} = -eE_x = e \frac{\partial V}{\partial x}
\]

(2-4)

From which the electron velocity could be obtained as follows:
\[
\int_0^v dv_e = \frac{e}{m_e} \left( \frac{\partial V}{\partial x} \right) \int_0^t dt
\]

\[
v_e = \frac{e}{m_e} \frac{dV}{dx}
\]

\[(2-5)\]

A static uniform magnetic field will not change the velocity of the charged particle but will force the particle to gyrate in a fixed orbit around the magnetic field line. The force equation for a charged particle under the influence of magnetic field is

\[
F_m = q_i (v \times B)
\]

\[(2-6)\]

Where \(F_m\) is the magnetic force, \(q_i\) is the charge (for an ion). The force \(F_m\) (Lorenz force) is always normal to both \(B\) field vector and \(v\) velocity component normal to the magnetic field. Charged particles’ trajectories are governed by the electric and magnetic fields (if both does exist), and the spatial and temporal dependence of these fields (if any)\(^{22}\).

The motion of a charged particle due to electric force may be expressed by electrostatic radius of refraction, which is proportional to the particle's kinetic energy. The orbiting radius due to magnetic force is proportional to the particle’s momentum. The electric deflection is given by:

\[
-eE_n = \frac{mv^2}{r_n}
\]

\[
r_n = \frac{mv^2}{-eE_n} = -\frac{(m/e)v^2}{eE_n} = \frac{-2(KE)}{eE_n}
\]

\[(2-7)\]

The gyration radius due to magnetic field is given by:
\[ -B_n e v = \frac{mv^2}{r_n} \]
\[ r_n = \frac{mv}{eB_n} = \frac{(m/e)v}{B_n} = \frac{(2m)^{1/2}(KE)^{1/2}}{eB_n} \]  \hspace{1cm} (2-8)

Where \( KE \) is the kinetic energy \( \frac{mv^2}{2} \)

Thus all ions (or electrons) with the same starting location, direction and kinetic energy per unit charge would have identical trajectories in static electric and magnetic fields. The trajectories are not mass dependent in static electric field, but they are mass dependent in static magnetic field.

In this study, only electric field exists due to the applied potential between the cathode and anode, and thus it is the electric field that dominates the motion of the thermionic electrons.\textsuperscript{[23]} The distribution of the electric field will be determined by the shape of the focusing cup, the applied voltage on the filament and the focusing cup and the relative position of the anode to the cathode (i.e. the tilted angle of anode, distance from anode to cathode, etc). As seen in Figure 2-1, the focusing cup shapes the electron distribution leaving the filament and a negative bias voltage further restricts the electron distribution to achieve a smaller focal spot size.
2.3 X-Ray Generation and Interactions with Matters

2.3.1 X-ray generation

When fast electrons interact with matters, part of their energy is converted into electromagnetic radiation in the form of \textit{bremsstrahlung}. For monoenergetic electrons that slow down and stop in a given material, the bremsstrahlung energy spectrum is a continuum with photon energies that extend as high as the electron energy itself. The emission of low energy photons predominates and the average photon energy is a small fraction of the incident electron energy. When fast electrons interact with specific material, except for bremsstrahlung interaction, the other part of their energy knock out the orbital electrons in an atom from their normal orbits, as shown in Figure 2-2. There is a tendency for the electrons to rearrange themselves to return the atom from the excited state to its ground state. The energy liberated in the transition from the excited to the ground state
takes the form of a characteristic X-ray photon whose energy is given by the energy difference between the initial and final states, as shown in Figure 2-3.
Another form of x-ray is produced when a beam of energetic electrons is bent into a circular orbit. From electromagnetic theory a small fraction of the beam energy is radiated away during each cycle of the beam. When extracted from the accelerator in a tangential direction to the beam orbit, the radiation appears as an intense and highly directional beam of photons with energy that can span the range from visible light (a few \( eV \)) through x-ray energies (~10keV). Monochromators can be used to produce nearly monoenergetic photon beams with a very high intensity. The high intensity and tunable energy source is called synchrotron source.

2.3.2 X-ray interactions with matters

When X-ray radiation passes through an object, several types of interactions occur, including coherent scattering, photoelectric absorption, incoherent scattering (Compton scattering), pair production, photon disintegration, and scattering and diffraction.
Coherent scattering (Coh), also known as Rayleigh coherent, process neither excites nor ionizes the atom and the photon retains its original energy after the scattering event. Virtually no energy is transferred, but the direction of the photon is changed, the probability of coherent scattering is significant only for low photon energies (typically below a few hundred keV for common materials) and is most prominent in high-Z absorbers. The average deflection angle increases with decreasing energy.

Photoelectric absorption (PE) of x-rays occurs when the x-ray photon is absorbed and results in the ejection of electrons from the outer shell of the atom, which leaves the atom in an ionization state. Subsequently, the ionized atom returns to the neutral state with the emission of an x-ray characteristic of the atom. This subsequent emission of lower energy photons is generally absorbed and does not contribute to (or hinder) the image making process. Photoelectron absorption is the dominant process for x-ray absorption up to energies of about 500keV. Photoelectron absorption is also dominant for atoms of high atomic numbers.

Incoherent scattering (Incoh), also known as Compton Scattering, occurs when the incident x-ray photon ejects an electron from an atom and an x-ray photon of lower energy is scattered from the atom. Relativistic energy and momentum are conserved in this process (demonstrated in the applet below) and the scattered x-ray photon has less energy and therefore greater wavelength than the incident photon. Compton Scattering is important for low atomic number specimens. At energies of 100keV-10MeV the absorption of radiation is mainly due to the Compton Effect.
Pair Production (Pair) can occur when the x-ray photon energy is greater than 1.02MeV, when an electron and positron are created with the annihilation of the x-ray photon. Positrons are very short lived and disappear (positron annihilation) with the formation of two photons of 0.51MeV energy. Pair production is of particular importance when high-energy photons pass through materials of a high atomic number.

Below are other interaction phenomena that can occur. Under special circumstances these may need to be considered, but are generally negligible.

Photodisintegration (Trip) is the process by which the x-ray photon is captured by the nucleus of the atom with the ejection of a particle from the nucleus when all the energy of the x-ray is given to the nucleus. Because of the enormously high energies involved, this process may be neglected for the energies of x-rays used in radiography.

The relative probability of the five interactions for calcium is shown in Figure 2-5. It is seen that in the diagnostic imaging range, near 0.1MeV, photoelectric absorption dominates the interactions for born in the body. Coherent and incoherent scattering are the great majority of interactions for normal tissues in the body too. Pair productions can be neglected for the x-ray photons under 0.1MeV.
2.4 X-Ray Imaging

2.4.1 Conventional x-ray imaging

Conventional x-ray imaging is based on the attenuation of an x-ray as it travels through a medium, the density of the medium and the energy of the incident beam determine the attenuation coefficient. A medium with a structure of different compositions will attenuate the incoming beam with different attenuations. An x-ray film or imaging plate will indicate the structure of the medium. The intensity of x-ray $I$ after passing through the medium is related to the incident intensity $I_0$ by an exponential law with
negative exponent. The equation, Eq.(2-9), describes the relation between $I$ and $I_0$, the thickness of the medium $x$ and the attenuation coefficient of the medium $\mu$:

$$I = I_0 e^{\sum \mu x} \quad (2-9)$$

For human body, the concept is the same and radiography is a picture obtained due to different attenuations in the human body for a given exposure rate on the film or the detector. A basic radiography system has an x-ray generator on one side of the patient, and an x-ray detector on the other side. When x-ray travels through the body, the attenuation is different in different tissue or bones due to their difference in attenuation coefficients. The contrast on the film or amplitudes on a digital detector produce an image of the structure of the medium. Radiographic images in the medical practice are widely used to obtain images of broken bones, kidney stones, lung cancer, cardiovascular disorder, etc. Mammography is one of the radiography applications, because the linear attenuation coefficients of normal and cancerous tissue in the breast have little difference at the lower x-ray energy levels as shown in Figure 2-6.

The different attenuation coefficients of these tissues are not detectable with conventional radiography devices, which could use relatively high-energy x-ray. The spectrum of a conventional x-ray tube is shown in

Figure 2-7. The images from these energy ranges cannot efficiently discriminate between normal and cancerous breast tissues. As a corollary, modern mammography systems have x-ray source and detector systems specifically designed for breast imaging.
Figure 2-6 Linear attenuation coefficients for breast tissues and tissue-equivalent materials

(From Taibi, 2003)

Figure 2-7 Conventional X-ray tube spectrum

(From Taibi, 2003)
2.4.2 Diffraction Enhanced Imaging (DEI)

Conventional x-ray radiography uses an x-ray beam to penetrate an object, and the attenuation of x-ray occurs through the structure of the object resulting in different attenuated intensities. The difference in attenuation results in a spatial distribution of the attenuated x-rays on the film or the digital detector. However, x-ray attenuation process is not only due to interaction between the incident x-rays and an object, it also includes absorption, refraction and scattering. The scattering may include small angle, which is less than milliradians. Scattered beam contains information on the structure of the object, and such information is not obtainable in conventional radiography systems.

The phase radiography method is based on refraction radiation at the boundaries separating various media in an object. It is known that the refractive index of a medium \( n = 1 - \delta \), where \( \delta \) is the unit decrement of the refractive index

\[
n = \frac{e^2}{mc^2} \frac{N\lambda^2 Z \rho}{2\pi A}
\]  

(2-10)

Where \( \frac{e^2}{mc^2} \) is the classic electron radius, \( \lambda \) is the wavelength, \( N \) is Avogadro’s number and \( Z \) and \( A \) are the medium atomic number and weight, respectively. Thus, \( \delta \) is proportional to the medium density \( \rho \): \( \delta \approx 1.35 \times 10^9 \rho \lambda^2 \) where \( \lambda \) is expressed in meters and \( \rho \) in kg m\(^{-3}\).

In a flat boundary case, media with refractive indices \( n_1 \) and \( n_2 \) and an x-ray beam falling at an angle \( \alpha \) is shown in Figure 2-8(a). Due to refraction, and according to
Snell’s law, the beam deviates from its initial direction at an angle $\Delta \alpha \approx \Delta \delta \tan \alpha$, where $\Delta \delta = n_1 - n_2$ is the variation of the refractive index. The angle of deviation can become sufficiently large in the case of a curvilinear, for example a cylinder edge as shown in Figure 2-8(b). Here $\alpha$ tends to $\pi / 2$ and thus $\tan \alpha$ becomes large and could easily be more than 10. Since the unit decrements of refractive indices $\delta$ are about $10^{-5} - 10^{-6}$, the angles of refraction at the boundaries between media with close densities ($\Delta \delta \sim 10^{-2}$) become about $10^{-6} - 10^{-7}$ radian.

![Figure 2-8 Refraction of the x-ray beam at a boundary between media with refractive indices $n_1$ and $n_2$: (a) flat boundary; (b) curvilinear boundary. (From V. N. Ingal, 1998)](image)

Obviously, it is impossible to register beams deviated at such small angles in commonly used radiography. For this reason the equipment for phase radiography contain a special device initially providing a parallel (with less then $10^{-6}$ radian divergence) beam of unenergetic x-rays illuminating the investigated object, and a device generating the object image.$^{[28, 29]}$
Figure 2-9 illustrates the synchrotron setup used to obtain radiographs of an object and the addition of the crystal analyzer (Bragg or reflection geometry) used to implement the DEI system at the synchrotron source. In this setup, a Si (3 3 3) double crystal monochromater is used to select required x-ray energy range for the synchrotron beam, while for the DEI Bragg case setup the Si (3 3 3) crystal serves as the Bragg analyzer. As previously mentioned, information from x-ray scattering and diffraction are lost in conventional radiography. In diffraction-enhanced imaging DEI Bragg setup, with Si (3 3 3) Bragg analyzer, it allows for such information to be obtained. In this setup, either Si (1 1 1) or Si (3 3 3) could be used. The difference is the reflectivity curve; the reflectivity curve of Si (3 3 3) is narrower than that of Si (1 1 1), as shown in Figure 2-10.
It is important to mention that in both setups of Figure 2-9, a Si (3 3 3) double crystal monochromater is used, but the addition of a Si (3 3 3) Bragg analyzer is necessary for the DEI Bragg setup. To further clarify this necessity, for DEI imaging, diffracting the poly-energetic synchrotron to create a near monoenergetic-imaging beam generates the imaging beam. The imaging beam passes through the object as in conventional radiography but a matching crystal Bragg analyzer is placed between the object and the detector, and is set at or near the peak of the Bragg diffraction angle. The condition for diffraction from the Bragg analyzer limits the x-rays that can be diffracted into the detector and thus provides a high degree of scatter rejection, which results in obtaining an improved image contrast. The Bragg analyzer provides almost complete scatter rejection due to the fact that the analyzer only accepts narrow angles in the range of few micro radians. The Bragg analyzer provides the tools necessary to prepare and analyze x-ray beams traversing an object on the micro radian scale, and thus this Bragg analyzer is a
necessity for a DEI setup. The material of the crystal is typically silicon. The purity and perfection of these crystals have allowed many advances in x-ray diffraction techniques and in particular at synchrotron x-ray sources. The condition for x-ray diffraction from a crystal is met only when the incident beam makes the correct angle to the atomic lattice planes in the crystal for a given x-ray energy, or wavelength. When this condition is met, the beam diffracts from the planes over a narrow range of incident angles, which is called the Bragg diffraction. As the crystal is rotated around the axis parallel to the lattice plane and perpendicular to the incident beam direction, the intensity variation is referred as the rocking curve. The shape of this rocking curve is roughly triangular with the peak reflectivity approaching near 100%.

The intensity of x-ray, after penetrated an object in normal radiography, can be expressed by:

$$I_N = I_C + I_I + I_D + I_R$$  \hspace{1cm} (2-11)

Where, $I_N$ is the source of contrast at the detector plane. The portions of coherent scattering $I_C$ and incoherent scattering $I_I$, and the diffraction intensity is given by $I_D$, which arrives on the detector along with the portion of incident beam $I_R$ that has been affected by refraction and attenuated by absorption or extinction. $^{31, 32}$

In a DEI system, the portion of refracted beam $I_R$ will be separated from the other components and shows contrast based on refraction, absorption and extinction. The scattering components, $I_C$ and $I_I$, contribute to loss of contrast and spatial resolution, which can be improved by using a synchrotron source and a monochromater. Synchrotron
radiation offers high intensity and good natural collimation of the x-ray beam. The characteristics of synchrotron radiation make it possible to select a narrow wavelength by a crystal monochromater. In addition, the crystal diffraction optics could also be used to eliminate coherent $I_C$ and incoherent $I_I$ fractions. The crystal analyzer diffracts the x-ray, which is aligned within the angular acceptance (rocking curve, few micro radians), onto the detector and thus it is possible to remove the scatter contribution to the image. After eliminating the coherent $I_C$ and incoherent $I_I$ scattering portions, the incident beam has only the refracted portion $I_R$, which is very close to the initial direction.

In the DEI setup, two images are obtained depending on the position on the rocking curve. One image is the apparent absorption image, which is an actual image from direct transmission. The other is the refraction image, which is correlated to the gradient of the refractive index along the path of the x-ray through the object. To facilitate this, an example of two images of a phantom are obtained; one through an analyzer angel that is slightly greater than the peak angle of the rocking curve (higher side image), and one at lower than the peak angle (lower side image). The rocking curve and two DEI images are shown in Figure 2-11.
According to D. Chapman, the intensity diffracted by the analyzer is set as a relative angle $\theta_i$ from the Bragg angle $\theta_B$ where the angle between the incident beam and diffraction planes is $\theta_B + \theta_i$ and is given by

$$I_i = I_R R(\theta_B \pm \theta_i)$$  \hspace{2cm} (2-12)
Where $I_i$ is the intensity at relative angle $\theta_i$ from Bragg angle $\theta_B$, and is defined as the portion of the incident beam which has only been affected by refraction and attenuation by absorption and extinction, and $R(\theta)$ is the analyzer reflectivity function at angle $\theta$. The analyzer reflectivity function $R(\theta)$ is a function of the rocking curve. The beam intensities of the images $I_L$ taken on the lower side $\theta_L$ of the rocking curve and $I_H$ taken at the higher side $\theta_H$, can be expressed by Taylor expansion.

\[
I_L = I_R \left[ R(\theta_L) + \frac{dR(\theta_L)}{d\theta} \Delta \theta \right]
\]

\[
I_H = I_R \left[ R(\theta_H) + \frac{dR(\theta_H)}{d\theta} \Delta \theta \right]
\]

(2-13)

The analyzer reflectivity function $R(\theta)$ is an expression of the Taylor expansion. From the above two equations, the beam intensity composed of apparent absorption $I_R$, and the refraction image angle, $\Delta \theta_z$ can be obtained.

\[
I_R = \frac{I_L \left( \frac{dR(\theta_H)}{d\theta} \right) - I_H \left( \frac{dR(\theta_L)}{d\theta} \right)}{R(\theta_L) \left( \frac{dR(\theta_H)}{d\theta} \right) - R(\theta_H) \left( \frac{dR(\theta_L)}{d\theta} \right)}
\]

(2-14)

\[
\Delta \theta_z = \frac{I_H R(\theta_L) - I_L R(\theta_H)}{I_L \left( \frac{dR(\theta_H)}{d\theta} \right) - I_H \left( \frac{dR(\theta_L)}{d\theta} \right)}
\]
In general, the images of each side are obtained at the FWHM of the rocking curve. It makes \( R(\theta_h) \) and \( R(\theta_l) \) equal with the peak reflectivity normalized to 1.0. Because the rocking curve around the peak is symmetrical, one obtains:

\[
\frac{dR(\theta_h)}{d\theta} = -\frac{dR(\theta_l)}{d\theta} \tag{2-15}
\]

Therefore, \( I_R \) and \( \Delta \theta_z \) can be shown as

\[
I_R = I_L + I_H \tag{2-16}
\]

\[
\Delta \theta_z = \frac{0.5(I_H - I_L)}{\frac{dR}{d\theta}(I_H + I_L)}
\]

The \( \Delta \theta_z \) represents the distribution of refraction angles in the Z-direction. The refraction intensity is expressed by \( I_R \frac{dR}{d\theta} \Delta \theta_z \) and is proportional to \( (I_L - I_H) \), assuming that the slope of the rocking curve \( \frac{dR}{d\theta} \) is of equal magnitude at the high and low sides. As illustrated in Figure 2-11, by D. Chapman, 1997, the rocking curve FWHM is 4 micro radians. The figure also shows both high and low angles sides’ images.

The main components of DEI system are an image plate detector, a monochromater, Bragg analyzer, and a synchrotron radiation source. The DEI group (Zhong, Chapman, at al. 2000) have already established two DEI imaging test facilities using the synchrotron source at the National Synchrotron Light Source (NSLS) of Brookhaven National Laboratory for lower energy range (less than 30keV), and the Advanced Photon Source.
(APS) at Argonne National Laboratory for higher energy range (up to 60keV). The two DEI facilities successfully performed DEI imaging experiments.

Z. Zhong et al. [33] reported that the DEI images were obtained using image-plate readers (Fuji Medical Systems, model BAS2000 or AC3) at the NSLS. Since the Bragg analyzer inverts the beam, the image plate was scanned in the direction opposite to the object’s scanning direction to avoid blurring the image. The image plate scanner was also tilted to an angle $2\theta_B$ from the vertical direction. Pixel size of the image was $100\mu m \times 100\mu m$. Images are read at latitude of 4, and a sensitivity of 400 with 1024 grey levels.

The synchrotron source offers high intensity and good natural collimation of radiation, but it has a continuous spectrum through the entire energy range. The synchrotron radiation makes it possible to select a narrow energy range by a crystal monochromater. According to the experiment by Chapman, et al. at NSLS, a silicon double-crystal monochromater was used for selecting narrow radiation energy range. The energy range of the system was 16-25keV. The beam energy used 18keV with an energy width of about 1.5eV. The monochromator crystals are silicon (3 3 3) lattice planes. The narrower rocking curve of the Silicon (3 3 3) makes a preferable choice. This choice of lattice planes increased the sensitivity to refraction effects by a factor of five as compared to an experiment that used the silicon (1 1 1) lattice planes. [34]

The x-ray flux of the synchrotron affect the DEI image quality and scan time. According to Z. Zhong, et al., the X15A beam line at NSLS has a flux of
$1.4 \times 10^{12} \text{ph/s/mm}^2/\text{keV}$ at 18keV (at 200mA ring current) of white beam. This white beam travels thorough a beryllium window and aluminum filter, protected from ozone by a helium flow. After the white beam travels through the beryllium window and the aluminum filter, the specific energy range could be selected by the monochromator. The monochromatic beam is dependent on the crystal diffraction plane. Results of the monochromatic beam, using Si (1 1 1), Si (3 3 3), Si (4 4 4) and Si (5 5 5) are shown in Figure 2-12.

![Figure 2-12 Monochromatic beam flux in the NSLS X15A hutch using silicon [1 1 1], [3 3 3], [4 4 4] and [5 5 5] crystal-diffraction planes (Ref.: Z. Zhong 2000).](image)

As previously mentioned, the white beam from X15A beam line at NSLS has $1.4 \times 10^{12} \text{ph/s/mm}^2/\text{keV}$ at 18keV. The scan time, which used this white beam intensity, was 4 to 200 sec. For the purpose of using DEI for mammography, this scan time is
appropriate. However, using synchrotron source is not feasible for a clinical DEI system unless DEI facilities to be built at a national laboratory that has a synchrotron source. The size, construction cost, and the operation of a synchrotron source are difficulties of applying a synchrotron as an x-ray source for clinical application. A conventional x-ray tube may be used to substitute for the x-ray source. However, conventional x-ray tubes do not specifically provide the characteristics needed for DEI systems. Conventional x-ray tubes have continuous spectrum and low beam intensity as compared to synchrotron sources. The bremsstrahlung radiation from a conventional x-ray tube delivers unnecessary radiation dose to the patient, and dose not provide a means by which DEI could be employed. Moreover, the low intensity of the produced x-ray increases the scan time, which is estimated to be approximately between 1,000 to 10,000 seconds for a conventional source. Such long scanning times are not acceptable to operate a DEI system for clinical use for mammography. It is also important to have a collimated x-ray beam to provide area magnification for DEI application. A conventional x-ray tube has typically 0.3~0.4 mm focal spot. For a clinically approved DEI mammography unit, the dimension of the beam in the sagittal direction will be 150 mm to get a full field of view. For these reason, a new x-ray source is needed to provide the similar synchrotron characteristics necessary for DEI imaging at clinical practice level.

Several concepts for a new x-ray source were proposed by the NCSU research group (Bourham, Doster, Verghese and Sayers, in collaboration with UNC Chapel Hill Radiology group and others, 2000), such as the shaped-target multi-filament concept, the high-current beam steering concept and the cold cathode field emission concept. The
shaped-target multi-filament concept has the most attractive features over other concepts. In this concept, the source design is based on a tilted stationary molybdenum target with the target’s surface shaped in a log-spiral. Filaments to be arranged as an array of line filaments, with each filament assembly composed of the individual line filaments and corresponding focus cups. Total emission current of the filament array can be as high as 3A, which will deliver a total power of 180 kW to the target for 60kVp accelerating potential. The illumination area for this concept is 150x150 mm, however, a 50x50 mm prototype was proposed.

Increasing the acceleration potential produces higher x-ray intensity, however, generated bremsstrahlung radiation could be reduced and eliminated through aluminum or a beryllium filter. Increasing the electron beam current, which depends on electron emission area from the filament, also increases the x-ray intensity. The typical x-ray tube uses a small filament (point source), which does not exceed the diameter of the target area. Therefore, the concept of long-line filament to produce larger electron emission, as the emission area increases, is an attractive option over the standard source. The larger electron emission area produces higher electron beam current, and higher electron flux, thus increasing the number of electrons illuminating the target over the entire target cross section. Both methods, increasing acceleration potential and using larger electron emission area, result in increased heat loading of the x-ray target. The heat loading would exceed the capacity of cooling mechanism of typical x-ray tube, which usually uses a rotating target to spread the heat loading or uses an air-cooling system. Therefore, a long-line filament x-ray source will necessitate an active cooling system for heat removal.
2.5 Heat Transfer

2.5.1 Heat Production

When accelerated electrons embark on the x-ray target, 99% of their kinetic energy is converted to target heating. With increased operation time, the temperature of the target could increase beyond the melting point. In the target, the main heat transfer is conduction, although the target would re-emit heat via radiation at a very slow rate as the entire source is under high vacuum, around $10^{-6}$ Torr, and there is no flow regime to allow for efficient convection. The target material properties and its geometrical shape are important factors in thermal management analysis. The target is a thin layer of molybdenum on top of oxygen-free cylindrical copper block. Molybdenum melting point is $2623^\circ$C while it is much higher than that of copper $1085^\circ$C, and thus the copper block will reach melting point if heat loading is intensive.

The heat production at the target could be calculated from the efficiency of the x-ray production \(^{135}\) (J. Selman, 2000). The efficiency of x-ray production is directly proportional to the atomic number of the target and the applied potential, as approximately expressed by the following equation:

$$\text{%efficiency} = K \times Z \times kVp \quad (2-17)$$

Where $K$ is constant=$1\times10^{-4}$, $Z$ is the atomic number of the target, and $kVp$ is the peak high voltage. For example, for a molybdenum target ($Z=42$) and an accelerating potential of $30$ kVp, the efficiency would be:
\[ \%_{\text{efficiency}} = 1 \times 10^{-4} \times 42 \times 30 = 0.125\% \]  \hspace{1cm} (2-18)

This means that only 0.125\% of the total kinetic energy of the electron beam appears as x-ray and the remaining 99.875\% as heat in the target.

2.5.2 Heat Transfer

The mechanism of heat transfer into the target has the three heat transfer processes, conduction, convection, and radiation; and they occur simultaneously depending on the medium. In x-ray targets, the conduction would be dominant among convection and radiation heat transport because the source is under vacuum. However, radiation heat transfer from the hot target follows. In this research, a molybdenum layer is attached to the oxygen-free copper target, where the later serves as a target structure and cooling material. The target design, shown in Figure 2-13, is a one cylinder with two sections of different diameters. The target has an internal cylindrical channel to allow for active cooling (water or liquid nitrogen). The front side of the target is covered with a thin layer of molybdenum prepared by sintering. Hence, the temperature of that molybdenum surface could be considered as the saturated temperature of water or liquid nitrogen at operating pressure.
The general heat conduction equation is given by

$$\nabla \cdot k(T)\nabla T + q \cdot \vec{r} (r, t) = \rho C_p \frac{\partial T}{\partial t}$$  \hspace{1cm} (2-19)

Where $T$ is the temperature (°K), $\rho$ is the target material specific density (kg/m$^3$), $k$ is the thermal conductivity (W/m°K), $C_p$ is the specific heat (J/kg°K) and $q \cdot \vec{r}$ is the volumetric heat generation rate (J/m$^3$.s)$^{[36]}$

In this case, the 2-D, time dependent heat conduction equation in cylindrical geometry is given by

$$\frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial T}{\partial r} \right) + \frac{\partial^2 T}{\partial z^2} + q \cdot \vec{r} (r, t) = \rho C_p \frac{\partial T}{\partial t}$$  \hspace{1cm} (2-20)

Solution of the heat conduction equation, subject to appropriate boundary and initial conditions gives the target’s temperature distribution. Compared with the copper block, the molybdenum layer is very thin, even though the thermal conductivity of molybdenum
is about a factor of 4 higher than that of copper, the thermal resistance of molybdenum could be neglected in this analysis. The initial temperature is actually the room temperature.

In order to perform thermal analysis, electron beam energy and the beam profile at the front surface of the target must be used as inputs to the thermal analysis code. The choice of beam profile is based on the results of the SIMION code. COMSOL multiphysics software package (thermal module) was used to computationally manage the target thermal analysis.

2.6 Dose Evaluation

Radiation shielding is an important issue for the safe operation of any x-ray device, even for low energy x-ray systems. When radiation particles travel through matter, the radiation hazard is measured by energy imparted per unit mass in medium. If an incremental volume of tissue $\Delta V$ around a given point in space has mass $\Delta m$ and the energy imparted to it by ionizing radiation is $\Delta E$, the absorbed dose $D$ in the given tissue at this point is defined by

$$D = \lim_{\Delta V \to 0} \left( \frac{\Delta E}{\Delta m} \right)$$

(2-21)

If to define $\varepsilon$ as the average amount of energy transferred from the primary radiation field to the medium in a single interaction, it is easy to see that $\Delta E$, the amount of energy transferred per unit time to the medium due to all interactions within $\Delta V$, is given by
\[ \Delta E = \varepsilon \sigma N \Phi \Delta V \]  \hspace{1cm} (2-22)

Where \( \sigma \) is defined as the probability of the interaction (microscopic cross section per atom), \( N \) is the number of atoms per unit volume of the medium and \( \Phi \) is the flux density in number of particles per \( \text{cm}^2 \).

If the mass of the incremental volume is given by \( \rho \Delta V \), where \( \rho \) is the density of material in \( \Delta V \), then the detector response of the absorbed dose is

\[ R \equiv \frac{\Delta E}{\rho \Delta V} = \varepsilon \frac{\sigma N}{\rho} \phi \]  \hspace{1cm} (2-23)

Generalization of this formula to take into account a distribution of particle energies and mixture of types of atoms, as well as the fact that \( \varepsilon \) will differ for different types of interactions, results in the following equation.

\[ R \equiv \int_0^\infty dE \mathfrak{R}(E) \phi(E) \]  \hspace{1cm} (2-24)

Where \( \mathfrak{R}(E) = \frac{\sigma N}{\rho} \).

The total absorbed dose of photon flux could be calculated by integrating over all energy ranges.\(^{37,38}\)

In dealing with the fundamental behavior of biological material or organisms subjected to radiation, one needs to take into account variations in the sensitivity of the biological material to different types or energies of radiation. For this purpose, quality factor \( Q \) is defined for each type and energy of radiation. The product of the quality factor
and the absorbed dose is identified as the dose equivalent and is recognized as an appropriate measure of radiation risk when applied in the context of establishing radiation protection guidelines and dose limits for population groups. According to ICRU 1986, the quality factor of photons is one unit. Hence the dose equivalent $H$ of x-ray is given by

$$H(rem) = D(rad) \times Q = D \times 1$$

(2-25)

The value of absorbed dose equals to that of dose equivalent for photon.

The objective of radiation shielding is to decrease the radiation flux or flux rate, that is $\Phi$. When radiation photon penetrates a material, flux intensity decreases exponentially. The photon flux-to-dose rate conversion factor is as shown in Figure 2-14. For this study, x-ray energy is lower than 30keV; photon flux-to-dose rate conversion factor of lower energy photons is shown in Figure 2-15.
Figure 2-14 Photon flux-to-dose rate conversion factors [Ref: ICRP-21]

Figure 2-15 Photon flux-to-dose rate conversion factors in low energy range [Ref: ICRP-21]
3 Computational Simulation

The whole x-ray generator system and the key components are shown at the beginning of this chapter. The electron trajectories, target thermal analysis, x-ray output window options, dose analysis and DEI imaging analysis are discussed in detail.

3.1 Design of Line X-Ray Source Generator

The key components of the designed line x-ray source generator are the filament-target assembly, which is installed in a six inch, six-way steel vacuum cross. Measuring instrumentation includes thermocouples attached to the target, a Faraday cup that can be moved along the target to measure electron distribution, a filament power supply, a high voltage power supply, an air-cooled turbomolecular pump venting to a rotary vane pump, vacuum measuring instruments (Convection and thermionic vacuum gauges), and current and voltage meters.

Figure 3-1 shows a schematic of the experiment. The filament-target assembly is composed of two parts, one is the grooved backing plate (filament cup) with a coiled tungsten filament as shown in Figure 3-2, and the other part is the target, which is an oxygen-free copper cylinder with coated with a thin layer of molybdenum, as shown in Figure 3-3.
Figure 3-1 Schematic diagram of the principle-proof experimental setup
Figure 3-2 Filament cup assembly (Units: cm)
(a) Side-view looking A-A' (b) Top-view (c) Side-view looking B-B'}
3.2 Simulation of Electron Trajectories

3.2.1 Calculation of Thermionic Electron Current Density

The electron current density is one of the main specifications of x-ray generator. It shows that how many electrons generate per mm$^2$ per second. Based on the Richardson-Dushman law, from Equation (2-2), the electron current density is a function of the metal’s work function and the metal’s surface temperature. If the strength of the electric field is lower than $1 \times 10^9 V \cdot m^{-1}$, the field-enhanced thermionic emission could be used (Schottky effect).

In this research, tungsten filament was used, which has a work function $W = 4.32eV^{[40]}$. The high voltage applied on the cathode is either -30 kV or -60kV, for
two study cases. The distance from the cathode to the anode is approximately 1cm. Hence the electric field near the cathode is around $E_c = 3 \times 10^6 \text{V} \cdot \text{m}^{-1}$. The values of $\Delta W$ are $0.065881\text{eV}$ and $0.09317\text{eV}$, for -30kV and -60kV cases, respectively. Given all the values of those parameters in Equation (2-2), one can get a table of filament temperature versus thermionic electron current density.

$$J = AT^2 e^{-\frac{(W-\Delta W)}{kT}}$$

Where $A$ is Richardson’s constant $=1.20173 \times 10^6 \frac{A}{m^2 K^2}$, $T$ is the tungsten filament surface temperature in °K, $W$ is the work function of tungsten $= 4.32\text{eV}$, $k$ is Boltzmann’s constant $= 8.617339 \times 10^{-5} \text{eV} \cdot \text{K}^{-1}$, and $\Delta W = 0.065881\text{eV}$ and $0.09317\text{eV}$ for -30kV and -60kV, respectively.

The filament is 0.127cm in diameter and 2.032cm in length. The total surface area of the filament is 0.81cm$^2$. The total electron current (beam current) can be calculated from the thermionic emission current density and the filament emitting surface area. The number of electrons generated by the filament at a given temperature is given by

$$N = \frac{J(C/(\text{mm}^2 \cdot \text{s}))}{1.60218 \times 10^{-19} (C)} = \#\text{electrons}/(\text{mm}^2 \cdot \text{s})$$

The melting point of tungsten is 3695°K, thus the filament operating temperature must not reach the melting point. Table 3-1 shows the calculation of the current density, electron flux and beam current for the temperature range between 1800-3100°K, indicating that a
beam current of 3.73A would be obtained at a filament temperature of 2600°K when the
accelerating potential is -30kV. If to increase the accelerating potential to -60kV, the
beam current would be 4.22A at same filament temperature, as shown in Table 3-2.
Hence, for an upscale device to generate a beam current of 3A (industrial scale model) the
filament temperature will always be less than 2600°K in both test cases of -30 or -60kV
accelerating potential. The desired photon flux for DEI application will be determined by
the beam current and accelerating potential. Figure 3-4 shows the electron beam current
versus photon flux for a molybdenum target at –60kV.

<table>
<thead>
<tr>
<th>Filament Temperature (K)</th>
<th>Current Density (A·mm⁻²)</th>
<th>Electron Flux #electrons/(mm²·s)</th>
<th>Beam Current (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1800</td>
<td>4.78E-06</td>
<td>2.99E+13</td>
<td>3.87E-04</td>
</tr>
<tr>
<td>1900</td>
<td>2.25E-05</td>
<td>1.41E+14</td>
<td>1.83E-03</td>
</tr>
<tr>
<td>2000</td>
<td>9.16E-05</td>
<td>5.72E+14</td>
<td>7.42E-03</td>
</tr>
<tr>
<td>2100</td>
<td>3.27E-04</td>
<td>2.04E+15</td>
<td>2.65E-02</td>
</tr>
<tr>
<td>2200</td>
<td>1.05E-03</td>
<td>6.53E+15</td>
<td>8.47E-02</td>
</tr>
<tr>
<td>2300</td>
<td>3.03E-03</td>
<td>1.89E+16</td>
<td>2.45E-01</td>
</tr>
<tr>
<td>2400</td>
<td>8.07E-03</td>
<td>5.04E+16</td>
<td>6.54E-01</td>
</tr>
<tr>
<td>2500</td>
<td>1.99E-02</td>
<td>1.25E+17</td>
<td>1.61E+00</td>
</tr>
<tr>
<td><strong>2600</strong></td>
<td><strong>4.61E-02</strong></td>
<td><strong>2.88E+17</strong></td>
<td><strong>3.73E+00</strong></td>
</tr>
<tr>
<td>2700</td>
<td>1.00E-01</td>
<td>6.28E+17</td>
<td>8.13E+00</td>
</tr>
<tr>
<td>2800</td>
<td>2.07E-01</td>
<td>1.30E+18</td>
<td>1.68E+01</td>
</tr>
<tr>
<td>2900</td>
<td>4.09E-01</td>
<td>2.55E+18</td>
<td>3.31E+01</td>
</tr>
<tr>
<td>3000</td>
<td>7.71E-01</td>
<td>4.82E+18</td>
<td>6.25E+01</td>
</tr>
<tr>
<td>3100</td>
<td>1.40E+00</td>
<td>8.75E+18</td>
<td>1.13E+02</td>
</tr>
</tbody>
</table>
Table 3-2 Filament Temperature versus Electron Flux at -60kV

<table>
<thead>
<tr>
<th>Filament Temperature (K)</th>
<th>Current Density ($A \cdot mm^{-2}$)</th>
<th>Electron Flux (#electrons/(mm$^2 \cdot s$))</th>
<th>Beam Current (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1800</td>
<td>5.70E-06</td>
<td>3.56E+13</td>
<td>4.61E-04</td>
</tr>
<tr>
<td>1900</td>
<td>2.66E-05</td>
<td>1.66E+14</td>
<td>2.16E-03</td>
</tr>
<tr>
<td>2000</td>
<td>1.07E-04</td>
<td>6.71E+14</td>
<td>8.69E-03</td>
</tr>
<tr>
<td>2100</td>
<td>3.80E-04</td>
<td>2.38E+15</td>
<td>3.08E-02</td>
</tr>
<tr>
<td>2200</td>
<td>1.21E-03</td>
<td>7.54E+15</td>
<td>9.78E-02</td>
</tr>
<tr>
<td>2300</td>
<td>3.48E-03</td>
<td>2.17E+16</td>
<td>2.82E-01</td>
</tr>
<tr>
<td>2400</td>
<td>9.21E-03</td>
<td>5.75E+16</td>
<td>7.46E-01</td>
</tr>
<tr>
<td>2500</td>
<td>2.26E-02</td>
<td>1.41E+17</td>
<td>1.83E+00</td>
</tr>
<tr>
<td><strong>2600</strong></td>
<td><strong>5.21E-02</strong></td>
<td><strong>3.25E+17</strong></td>
<td><strong>4.22E+00</strong></td>
</tr>
<tr>
<td>2700</td>
<td>1.13E-01</td>
<td>7.06E+17</td>
<td>9.14E+00</td>
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<tr>
<td>2800</td>
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<td>1.45E+18</td>
<td>1.88E+01</td>
</tr>
<tr>
<td>2900</td>
<td>4.56E-01</td>
<td>2.85E+18</td>
<td>3.69E+01</td>
</tr>
<tr>
<td>3000</td>
<td>8.57E-01</td>
<td>5.36E+18</td>
<td>6.94E+01</td>
</tr>
<tr>
<td>3100</td>
<td>1.55E+00</td>
<td>9.70E+18</td>
<td>1.26E+02</td>
</tr>
</tbody>
</table>

Figure 3-4 Electron beam current versus photon flux for a Mo target at ~60kV
### 3.2.2 Electron Trajectories

The target tilt angle affects the electric field distribution between the cathode and the anode, which influences the electron trajectories and the focal size of generated x-ray. The geometrical configuration of the proof-of-principle experiment allows for a maximum of 22.5° degree tilt angle, as shown in Figure 3-5.

![Figure 3-5 Schematic of the filament and target positions in the proof-of-principle experiment, the maximum allowable tilt angle is \( \theta = 22.5^\circ \) in this geometry\(^41\)](image)

Simulation of electron trajectories was performed for two potential options with each option simulated at three tilt angles, 0, 15 and 22 degrees. The first configuration option has the filament acting as a cathode and biased at -12V while the filament cup is at -30kV. The second option has the filament acting as a cathode and biased at -12 V while the filament cup is at -60kV. In all simulations, 1100 electrons were flown from the
filament towards the target. A geometry input program for use with SIMION code was written and is listed in Appendix A.

SIMION code simulation provides spatial distribution of electrons as they land on the surface of the target. Axis transformation is required as the target could be tilted to change the takeoff angle. The axis transformation makes it possible to obtain 2-D information from 3-D data. The trajectories are shown in Figure 3-6 through Figure 3-8. Figure 3-9 through Figure 3-14 show 3-D plots and 2-D plots of electron distribution along x-axis and y-axis for all above-mentioned cases.

In Figure 3-6, the target tilt angle is $0^\circ$ and the electrons are mostly focusing on the target in a rectangular shape determined by the length of the filament and the divergence angle at the end of the focusing cup, this forming a rectangular illumination of the target. This is expected because the electric field lines between the filament and the target are almost straight lines and thus electron trajectories will follow the field lines, also seen from the figure that only one electron escaped outside the focusing area. Changing the target tilt angle to $15^\circ$ resulted in a slight widening of the illumination area on the target without any major particle loss as seen from Figure 3-7. Increasing the target tilt angle to its maximum of $22^\circ$ increases the illumination area on the target, while not much, but it is sufficiently enough to generate an area beam from a line source with minimum particle loss, as shown in Figure 3-8.
Figure 3-6 Trajectory of electrons with target at 0° tilt angle

Figure 3-7 Trajectory of electrons with target at 15° tilt angle

Figure 3-8 Trajectory of electrons with target at 22° tilt angle

The frequencies of electrons landing on the target at 0° tilt angle are shown in Figure 3-9 and Figure 3-10 for –30 and –60kV accelerating potential, respectively. The
frequency peak is wider in the x-axis direction in the -30kV case than that of the -60kV one, and is almost the same in the y-axis direction in both cases. This is expected because increasing the accelerating potential intensifies the electric field intensity, and thus electrons are focused towards the center. The entire electron landing area is rectangular with the focused electrons approximate in a square shape.

Figure 3-9 Electron distribution on the target for a 0° tilt angle at -30kV potential

Figure 3-10 Electron distribution on the target for a 0° tilt angle at -60kV potential
The frequencies of electrons landing on the target at 15° tilt angle are shown in Figure 3-11 and Figure 3-12, for −30 and −60kV, respectively. The frequency peak in this case is sharper in the y-axis direction as compared to that of the 0° case due to the non-uniform electric field distribution. Although the rectangular shape is maintained, in principle, however the shape is narrower but still spreading in the x-axis direction, the effective shape is more of a ‘thick’ line in both the -30kV and -60kV cases.

Figure 3-11 Electron distribution on the target for a 15° tilt angle at -30kV potential

Figure 3-12 Electron distribution on the target for a 15° tilt angle at -60kV potential
When increasing the target tilt angle to 22°, the frequency peaks become much sharper in y-axis direction and almost with same spreading manner in the x-axis direction in both the –30kV and -60kV cases. The electron landing area still has the general rectangular shape but electrons are more concentrated in the middle and form a near-thick line shape, as shown Figure 3-13 and Figure 3-14.

**Figure 3-13** Electron distribution on the target for a 22° tilt angle at -30kV potential

**Figure 3-14** Electron distribution on the target for a 22° tilt angle at -60kV potential
The important role of electron trajectories simulation is to find out the optimum target illumination that can produce a near-rectangular area to allow for the production of an area x-ray beam from a long line filament source. Each landing spot is a spot that generates x-ray, and thus the entire electron distribution on the target represents the distribution of generated x-ray from the target. Because the electron distribution on the target is used as an input to the MCNP code to calculate the generated photon flux, the distribution of electrons should be abstracted by related distribution functions. In Figure 3-15 and Figure 3-16, the normalized relative frequencies of electrons along x-axis and y-axis are fitted with two normal distributed functions. Hence, in the input to MCNP simulation code, in SOUCRE CARD, the electron source definition should use an area source definition, the obtained distribution functions along x-axis and y-axis as given by Eq (3-1). These two distribution functions were used in the MCNP code to obtain the probability distribution of x-ray generation.

![Figure 3-15 Relative electron frequency along y-axis](image.png)
3.3 Simulation of X-ray Window Options

The filament-target assembly is placed inside the 6-inch, 6-way vacuum chamber; the target tilt angle provides extraction through the vacuum port opposite to the target. The vacuum port has a glass window, which serves as a vacuum sealing and viewing window. Because the system runs under high vacuum conditions, a thin beryllium or aluminum filter wouldn’t survive. The idea of coating the interior of the glass window with filtering material, by plasma cathodic arc techniques or other sputter deposition techniques, would provide the thinnest possible filter while maintaining the structure integrity under high vacuum conditions. Thus, one main function of the glass window is to hold high vacuum,

\[
\begin{align*}
  f(x) &= 0.22 \cdot e^{-\frac{(x-1.5)^2}{0.2}} \\
  f(y) &= 0.75 \cdot e^{-\frac{(y-1.45)^2}{0.03}}
\end{align*}
\]
and the other main function is to eliminate the low energy x-ray, which has no contribution to x-ray imaging contrast and quality, but increases the absorption dose of imaging objects. Therefore the objective of this simulation is to find the optimum window option, which can eliminate low energy x-ray but doesn’t attenuate the intensity of characteristic x-ray.

The MCNP simulation geometry is shown in Figure 3-17. The interior surface of the glass-viewing window is coated with a thin layer of metal film. The detector is placed outside of the glass window and recording the x-ray spectrum. The MCNP code input files for all window options simulations are listed in Appendix B-1.

![Figure 3-17 Diagram of the MCNP window simulation geometry](image)

Although the target in the prototype experiment is molybdenum (thin layer sintered on oxygen-free target), however, the simulation of the window was performed for three different targets, molybdenum, rhodium, and tungsten. The characteristic x-ray of the three target materials is shown in
The window options include glass window, graphite window, glass window with thin layer of rhodium film (two different simulations for 0.001mm and 0.01mm layer thickness), and glass window with 0.001mm thin layer of other material film, specifically aluminum, beryllium and molybdenum. For each case, the simulation was performed for two different beam currents, 0.3 and 3.0A. The 0.3A case is for implementation and benchmarking the lab-bases prototype system while the 3.0A case is for scalability predictions for an industrial clinically approved system.

The MCNP simulation results for the intensity of characteristic x-rays for each window material and thickness, for different target materials at 0.3 and 3.0A electron beam, are listed in Table 3-4 and Table 3-5, respectively, and are graphically plotted in Figure 3-18 and Figure 3-19. The indicated thickness of Rh, Mo, Al and Be represent the coating thickness on the glass, and thus the first column in Table 3-4 and Table 3-5 represent the metal layer thickness additional to the glass window thickness. These simulation results show that a graphite window would attenuate minimum amount of characteristic x-ray
among all window options. Increasing the accelerating potential from -30 to -60kV increases the intensity of characteristic x-ray by almost an order of magnitude for a molybdenum target, and close to two orders of magnitude for a rhodium target. For a tungsten target at 100kV accelerating potential, the intensity of characteristic x-ray is less than that of molybdenum and rhodium.

Table 3-4 Intensity of characteristic x-ray for a 0.3A electron beam for different target materials and different window options

<table>
<thead>
<tr>
<th>Material and thickness</th>
<th>Mo 30kV</th>
<th>Mo 60kV</th>
<th>Rh30kV</th>
<th>Rh60kV</th>
<th>W100kV</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.001Rh + 2.65mm glass</td>
<td>2.57E+09</td>
<td>1.43E+10</td>
<td>3.81E+09</td>
<td>2.59E+10</td>
<td>6.13E+09</td>
</tr>
<tr>
<td>0.001Mo + 2.65mm glass</td>
<td>2.92E+09</td>
<td>1.52E+10</td>
<td>3.44E+09</td>
<td>2.34E+10</td>
<td>6.05E+09</td>
</tr>
<tr>
<td>0.001Al + 2.65mm glass</td>
<td>2.71E+09</td>
<td>1.46E+10</td>
<td>3.70E+09</td>
<td>2.51E+10</td>
<td>5.95E+09</td>
</tr>
<tr>
<td>0.001Be + 2.65mm glass</td>
<td>2.67E+09</td>
<td>1.46E+10</td>
<td>3.75E+09</td>
<td>2.53E+10</td>
<td>6.49E+09</td>
</tr>
<tr>
<td>Glass (2.65mm thick)</td>
<td>3.13E+09</td>
<td>1.53E+10</td>
<td>3.22E+09</td>
<td>2.51E+10</td>
<td>6.15E+09</td>
</tr>
<tr>
<td>Graphite (2.65mm thick)</td>
<td>2.42E+10</td>
<td>1.27E+11</td>
<td>1.38E+10</td>
<td>9.94E+10</td>
<td>6.41E+09</td>
</tr>
<tr>
<td>0.01Rh + 2.65mm glass</td>
<td>1.98E+09</td>
<td>1.08E+10</td>
<td>3.22E+09</td>
<td>2.36E+10</td>
<td>5.73E+09</td>
</tr>
<tr>
<td>0.01Mo + 2.65mm glass</td>
<td>2.48E+09</td>
<td>1.30E+10</td>
<td>1.59E+09</td>
<td>1.09E+10</td>
<td>5.62E+09</td>
</tr>
<tr>
<td>0.01Al + 2.65mm glass</td>
<td>2.62E+09</td>
<td>1.45E+10</td>
<td>3.75E+09</td>
<td>2.48E+10</td>
<td>5.98E+09</td>
</tr>
<tr>
<td>0.01Be + 2.65mm glass</td>
<td>2.64E+09</td>
<td>1.46E+10</td>
<td>3.73E+09</td>
<td>2.54E+10</td>
<td>5.98E+09</td>
</tr>
</tbody>
</table>

Table 3-5 Intensity of characteristic x-ray for a 3.0A electron beam for different target materials and different window options

<table>
<thead>
<tr>
<th>Material and thickness</th>
<th>Mo 30kV</th>
<th>Mo 60kV</th>
<th>Rh30kV</th>
<th>Rh60kV</th>
<th>W100kV</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.001Rh + 2.65mm glass</td>
<td>7.26E+10</td>
<td>4.04E+11</td>
<td>1.08E+11</td>
<td>7.33E+11</td>
<td>1.73E+11</td>
</tr>
<tr>
<td>0.001Mo + 2.65mm glass</td>
<td>8.26E+10</td>
<td>4.29E+11</td>
<td>9.72E+10</td>
<td>6.61E+11</td>
<td>1.71E+11</td>
</tr>
<tr>
<td>0.001Al + 2.65mm glass</td>
<td>7.66E+10</td>
<td>4.13E+11</td>
<td>1.05E+11</td>
<td>7.11E+11</td>
<td>1.68E+11</td>
</tr>
<tr>
<td>0.001Be + 2.65mm glass</td>
<td>7.56E+10</td>
<td>4.12E+11</td>
<td>1.06E+11</td>
<td>7.17E+11</td>
<td>1.84E+11</td>
</tr>
<tr>
<td>Glass (2.65mm thick)</td>
<td>8.86E+10</td>
<td>4.33E+11</td>
<td>9.12E+10</td>
<td>7.10E+11</td>
<td>1.74E+11</td>
</tr>
<tr>
<td>Graphite (2.65mm thick)</td>
<td>6.83E+11</td>
<td>3.59E+12</td>
<td>3.90E+11</td>
<td>2.81E+12</td>
<td>1.81E+11</td>
</tr>
<tr>
<td>0.01Rh + 2.65mm glass</td>
<td>5.61E+10</td>
<td>3.04E+11</td>
<td>9.10E+10</td>
<td>6.69E+11</td>
<td>1.62E+11</td>
</tr>
<tr>
<td>0.01Mo + 2.65mm glass</td>
<td>7.01E+10</td>
<td>3.67E+11</td>
<td>4.49E+10</td>
<td>3.09E+11</td>
<td>1.59E+11</td>
</tr>
<tr>
<td>0.01Al + 2.65mm glass</td>
<td>7.42E+10</td>
<td>4.11E+11</td>
<td>1.06E+11</td>
<td>7.01E+11</td>
<td>1.69E+11</td>
</tr>
<tr>
<td>0.01Be + 2.65mm glass</td>
<td>7.46E+10</td>
<td>4.14E+11</td>
<td>1.06E+11</td>
<td>7.18E+11</td>
<td>1.69E+11</td>
</tr>
</tbody>
</table>
Figure 3-18 Intensity of characteristic x-ray with 0.3A electron beam

Figure 3-19 Intensity of characteristic x-ray with 3A electron beam
In this chapter, only x-ray spectrum with molybdenum target for different window options will be demonstrated. Simulation results using other targets, rhodium and tungsten, with all corresponding window options are shown in Appendix C.

Simulation results revealed that the glass-only window is able to eliminate all low energy x-ray spectra. The addition of a 0.001mm metal layer (all metal options: rhodium, molybdenum, aluminum or beryllium) has, apparently, no significant effect to eliminate low energy x-ray as shown in Figure 3-20. The case of 0.01mm metal layer on glass (all options) also shows that it is the glass that filters low-energy x-ray spectra, as shown in Figure 3-21.

![Figure 3-20 Spectrum comparison of 0.001mm thick layer of various metal films on glass window to glass-only window, accelerating potential is ~30kV](image-url)
A comparison between the x-ray spectra before and after the window for 0.001mm and 0.01mm rhodium coating on glass is shown in Figure 3-22 and Figure 3-23. It is obvious that the intensity of the 17.479keV $K_{\alpha1}$ is about a factor of 2 higher for the 0.001mm layer over the 0.01mm layer, which is expected due to attenuation through the increased thickness. Also observed from this simulation that the 0.001mm rhodium layer slightly reduced the very low energy x-rays, while the 0.01mm layer provided better reduction of low-energy x-rays. For this case of –30kV accelerating potential and 0.3A beam current, the photon flux is in the range of $10^9$ photons/mm²/sec, which is 2 orders of magnitude less than that of a synchrotron source. This, increasing the beam current by an order of magnitude, for an industrial scaled-up model, would result in increased flux by an order of magnitude. These simulation results are for a 5.746 cm² target and thus area
magnification would be necessary for an industrial device to produce a flux equivalent, or close to, a synchrotron source (~ $10^{12}$ photons/mm$^2$/sec), which implies that for an industrial scale device the target diameter would be 13.52cm, and the filament length would be 13.52cm long.

![Image of X-ray spectrum with Mo target, 0.001mm Rh + Glass window, -30kV]

**Figure 3-22** X-ray spectrum with Mo target, 0.001mm Rh + Glass window, -30kV

![Image of X-ray spectrum with Mo target, 0.01mm Rh + Glass window, -30kV]

**Figure 3-23** X-ray spectrum with Mo target, 0.01mm Rh + Glass window, -30kV
Similar results were obtained for molybdenum coating on the glass window, as shown in Figure 3-24 and Figure 3-25. The only difference is that the flux when using a molybdenum layer is higher than that for a rhodium layer.

Figure 3-24 X-ray spectrum with Mo target, 0.001mm Mo + Glass window, -30kV

Figure 3-25 X-ray spectrum with Mo target, 0.01mm Mo + Glass window, -30kV
In the aluminum case, it is obvious that aluminum does not reduce low-energy x-rays for the 0.001mm layer, but very slight reduction when using a 0.01mm layer. In general, similar results were obtained for the aluminum thin layer coating on the glass window, as shown in Figure 3-26 and Figure 3-27.

Figure 3-26 X-ray spectrum with Mo target, 0.001mm Al + Glass window, -30kV

Figure 3-27 X-ray spectrum with Mo target, 0.01mm Al + Glass window, -30kV
The beryllium case is very similar to the aluminum one, and does not reduce low-energy x-rays for both the 0.001 and 0.01mm layers, as shown in Figure 3-28 and Figure 3-29.

Figure 3-28 X-ray spectrum with Mo target, 0.001mm Be + Glass window, -30kV

Figure 3-29 X-ray spectrum with Mo target, 0.01mm Be + Glass window, -30kV
To test the glass-only and the graphite-only filtration, the MCNP was run for these cases, where it is obvious that a glass-only window dramatically eliminates low-energy x-rays while graphite-only reduces the low-energy x-rays but not at the same efficiency as glass, as shown in Figure 3-30 and Figure 3-31.

![Figure 3-30 X-ray spectrum with Mo target, Glass window, -30kV](image)

**Figure 3-30 X-ray spectrum with Mo target, Glass window, -30kV**

![Figure 3-31 X-ray spectrum with Mo target, graphite window, -30kV](image)

**Figure 3-31 X-ray spectrum with Mo target, graphite window, -30kV**
### 3.4 Simulation of Target Heat Loading

As previously mentioned in chapter 2, most of the energy carried by electrons imparting on the target will raise the target’s temperature and may exceed the melting point. Both the target material’s properties and geometrical shape affects the heat conduction behavior. The melting point of copper is 1358°K and the melting point of molybdenum is 2896°K. In this design of a copper target with a thin layer of molybdenum it will be assumed that the thermal resistance of the molybdenum is neglected, and thus the heat transfer will be computationally simulated for copper. Thus, the copper melting point of 1358°K will be the limiting temperature. The COMSOL Feblab7.0 software package chemical and heat transfer modules were used for the simulation of target heat loading under various conditions, such as low and high beam currents, low and high acceleration potentials, and active and inactive target cooling. Table 3-6 lists the heat flux on the target for various beam currents and operating potentials. A 3mA beam current was simulated for application to the lab-based prototype at accelerating potentials of 3, 30 and 60kV, and a 3.0A case at same accelerating potentials was also simulated to predict expected heat loading in an industrial scaled up device.

<table>
<thead>
<tr>
<th>Beam current</th>
<th>Acceleration potential</th>
<th>Total power</th>
<th>Average power</th>
</tr>
</thead>
<tbody>
<tr>
<td>3mA</td>
<td>3kV</td>
<td>9W</td>
<td>9.0kW/m²</td>
</tr>
<tr>
<td></td>
<td>30kV</td>
<td>90W</td>
<td>90.0kW/m²</td>
</tr>
<tr>
<td></td>
<td>60kV</td>
<td>180W</td>
<td>180.0kW/m²</td>
</tr>
<tr>
<td>3A</td>
<td>3kV</td>
<td>9.0kW</td>
<td>900kW/m²</td>
</tr>
<tr>
<td></td>
<td>30kV</td>
<td>90.0kW</td>
<td>9X10⁴kW/m²</td>
</tr>
<tr>
<td></td>
<td>60kV</td>
<td>180.0kW</td>
<td>1.8X10⁵kW/m²</td>
</tr>
</tbody>
</table>
The target geometry is imported from AUTOCAD to COMSOL multiphysics code, where in COMSOL the thermal loading input is the heat flux on the target (averaged over the distribution function) and the boundary conditions.

The first investigation is for the target thermal loading without active cooling. In this simulation case, the beam current was kept unchanged at 3.0mA; the accelerating potential was changed from -3 to -30 to -60kV, and simulation was carried out for 1800 seconds. Figure 3-32 shows the temperature distribution for the –3kV case, which shows that the target surface temperature doesn’t rise above ambient for such low beam current and –3.0kV potential. Boundary conditions are insulated boundaries and initial temperature is ambient.

Figure 3-32 Temperature distribution on the target after 1800s, 3mA beam current, and -3kV accelerating voltage
Increasing the accelerating potential to –30kV increases the target surface temperature to 406.2°K, as shown in Figure 3-33. Further increase in accelerating potential to –60kV increases the target surface temperature to 693°K, as shown in Figure 3-34.

Figure 3-33 Temperature distribution on the target after 1800s, 3mA beam current, and -30kV high voltage

Figure 3-34 Temperature distribution on the target after 1800s, 3mA beam current, and -60kV high voltage
These results show that operation of a lab-based prototype does not need any active cooling as the maximum temperature rise for -60kV accelerating potential is only 393°K higher than the ambient temperature after 1800 sec. Also, it is observed that there will be a hot spot at the center of the target surface for all simulation cases. This is because of the spatial distribution of the electrons imparting on the target, as previously shown in the electron trajectory simulation. For all simulation cases the highest temperature occurs at the center of the target’s front surface and the lowest is at back end of the target. A summary of simulation results for the 3mA case is shown in Table 3-7.

<table>
<thead>
<tr>
<th>Beam current</th>
<th>Accelerating potential (kV)</th>
<th>Operating time (sec)</th>
<th>Target’s front temp (°K)</th>
<th>Target’s back temp (°K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3mA</td>
<td>-3</td>
<td>1800</td>
<td>300</td>
<td>299.7</td>
</tr>
<tr>
<td></td>
<td>-30</td>
<td>1800</td>
<td>406.2</td>
<td>403.5</td>
</tr>
<tr>
<td></td>
<td>-60</td>
<td>1800</td>
<td>693</td>
<td>688</td>
</tr>
</tbody>
</table>

The second investigation is for the target thermal loading with active cooling, as the beam current will be increased to 3.0A to simulate the thermal conditions for a scaled-up device at the industrial level. In this simulation case, the beam current was kept unchanged at 3.0A; the accelerating potential was changed from -3 to -30 and simulation was carried out for 1800 seconds, while for the -60kV the simulation was only carried out for 90 sec. The active cooling for this simulation is by liquid nitrogen into the target block via a central channel. For practical systems, the liquid nitrogen would be circulated through a high vacuum fluid feedthrough connected to the inner channel inside the target.
block. The boundary conditions are insulated boundaries for the target outer surface, liquid nitrogen temperature inside the cooling channel, and initial temperature is ambient.

Figure 3-35 shows the temperature distribution for the −3kV case, which shows that the target surface temperature after 1800 sec is 183°K, while the back of the target block is at 80°K.

![Temperature distribution](image)

**Figure 3-35 Temperature distribution on the target after 1800s, 3.0A beam current, and -3kV high voltage with liquid nitrogen active cooling**

Increasing the accelerating potential to −30kV increases the target surface temperature to 1131°K in 1800 sec and increases the temperature of the back of the target’s block to 100°K, as shown in Figure 3-36. It is clear that operating such x-ray system, at 90kW power, will definitely necessitate active cooling. The front surface
temperature of 1131°K is still much lower than the melting point of the copper block (1356°K).

Figure 3-36 Temperature distribution on the target after 1800s, 3.0A beam current, And -30kV high voltage with liquid nitrogen active cooling

For increased accelerating voltage to -60kV, total of 180kW power, it is clear that the target temperature will rapidly rise in a shorter time. Simulation results show that the surface temperature will rise to 2183°K in only 90 sec, which is far exceeding the melting point of copper. The temperature of the back of the target block will still be cold enough as it will only rise to 200°K, as shown in Figure 3-37. Calculations have shown that safe operation for this case should be for a time not to 15 sec, during which the temperature only rises 1200 °K, which is less than the melting point of copper.
Figure 3-37 Temperature distribution on the target after 90s, 3.0A beam current, and -60kV high voltage with liquid nitrogen active cooling

For all simulation cases the highest temperature occurs at the center of the target’s front surface and the lowest is at the back end of the target. A summary of simulation results for the 3.0A case is shown in Table 3-8.

Table 3-8 Temperature of the copper target for 3.0A case

<table>
<thead>
<tr>
<th>Beam current</th>
<th>Accelerating potential (kV)</th>
<th>Operating time (sec)</th>
<th>Target’s front temp (°K)</th>
<th>Target’s back temp (°K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3A</td>
<td>-3</td>
<td>1800</td>
<td>183</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>-30</td>
<td>1800</td>
<td>1131</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>-60</td>
<td>90</td>
<td>2183</td>
<td>200</td>
</tr>
</tbody>
</table>
In order to benchmark the lab-based setup, an arrangement was made to install a disc target to allow for attaching three thermocouples to measure the temperature rise at different operational conditions. This disc target also facilitates the mapping of the electron distribution using a Farady cup. For this setup, only low voltage ranges were used for purpose of experimental conduct without actual generation of x-ray. This configuration helps to take safe measurements, obtain scalability and benchmark to code results. The disc target is made of aluminum, 10 cm in diameter and 0.5 cm in thickness, and the simulation was completed for accelerating potentials of 1.25, 1.5 and 2.5kV at 3mA beam current, for duration of 1800sec. The average heat source input for those cases is shown in Table 3-9. The heat flux input to the code is assumed uniform over the target surface.

<table>
<thead>
<tr>
<th>Beam current</th>
<th>Accelerating potential (kV)</th>
<th>Total power (W)</th>
<th>Average power density (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3mA</td>
<td>1.25</td>
<td>3.75</td>
<td>478</td>
</tr>
<tr>
<td></td>
<td>1.50</td>
<td>4.50</td>
<td>573</td>
</tr>
<tr>
<td></td>
<td>2.50</td>
<td>7.50</td>
<td>955</td>
</tr>
</tbody>
</table>

After 1800s, the temperature distributions on the target for those three cases are showing similar trend, as shown in Figure 3-38, Figure 3-39 and Figure 3-40. The highest temperature occurs at the center of the target and the lowest occurs at the edge. The temperature for these three cases is listed in Table 3-10. The temperature difference between the center and the edge of the target is about 0.2oK. This simulation will be compared to experimental measurements in Chapter 4.
Figure 3-38 Temperature distribution on the aluminum target after 1800s, 3mA beam current, and -1.25kV high voltage

Figure 3-39 Temperature distribution on the aluminum target after 1800s, 3mA beam current, and -1.5kV high voltage
Figure 3-40 Temperature distribution on the aluminum target after 1800s, 3mA beam current, and -2.5kV high voltage

Table 3-10 Temperature of the aluminum target after 1800s

<table>
<thead>
<tr>
<th>Beam current</th>
<th>Accelerating potential (kV)</th>
<th>Highest temp (°K)</th>
<th>Lowest temp (°K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3mA</td>
<td>1.25</td>
<td>303.8</td>
<td>303.7</td>
</tr>
<tr>
<td></td>
<td>1.50</td>
<td>305.9</td>
<td>305.8</td>
</tr>
<tr>
<td></td>
<td>2.50</td>
<td>314.4</td>
<td>314.3</td>
</tr>
</tbody>
</table>

3.5 Simulation of DEI Imaging

Generated x-ray travels through phantoms and then refracted by crystal analyzer before recorded by imaging plate. The analyzer could be Si (1 1 1), Si (3 3 3) or any other crystals. In this simulation, only Si (1 1 1) was considered. The rocking curves of Si (1 1 1) and Si (3 3 3) is as shown in Figure 3-41. The rocking curve of Si (3 3 3) is narrower than
that of Si (1 1 1). The diffraction angle can be transferred to energy of incoming x-ray with Bragg equation.

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

(3-2)

Where \( \lambda \) is wavelength of incoming x-ray, and \( K_{\alpha 1} \) is the characteristic x-ray of molybdenum 17.489keV, \( d \) is distance among layers of the given crystal, \( \theta \) is the diffraction angle in radians. By doing a transfer for Si (1 1 1) at 17.489keV, the x-ray energy versus crystal reflectivity could be plotted as shown in Figure 3-42.

![Rocking curves of Si (1 1 1) and Si (3 3 3) at 17.489keV](image)

**Figure 3-41** Rocking curves of Si (1 1 1) and Si (3 3 3) at 17.489keV
MCNP5 has one tally function, which allows user simulation of the x-ray or neutron imaging. Defining the x-ray source, the phantom geometry and the imaging plate, the phantom image could be obtained. This allows for comparison to experimentally obtained images. The mechanism of DEI simulation by using MCNP is to run a case with energy bin range at 17.439keV to 17.449keV as the DEI lower side image, then to run a second case with energy bin range at 17.475keV to 17.485keV as the DEI upper side image. As shown in Figure 3-42, reflectivity $R(\theta_L)$ at 17.439keV is 0.5 and reflectivity $R(\theta_H)$ at 17.489keV (i.e. peak of rocking curve) is 1.0. The slope of the rocking curve for higher and lower side is then given by $\frac{dR(\theta_H)}{d\theta} = 0$ and $\frac{dR(\theta_L)}{d\theta}$. Substituting into Eq(2-14), the refraction angle and absorption images could be obtained.
The first phantom is a 3 cm in diameter water sphere with one 1mm in diameter and 1mm in length calcium cylinder, and one 1 mm in diameter silicon sphere, as shown in Figure 3-43.

Simulation results of this phantom are shown in Figure 3-44. The low angle side and high angle side images are not clearly showing the interior details of the phantom. The refraction angle image (DEI image) clearly shows the boundaries of the objects inside the phantom.
In order to test the resolution of the images, a second phantom was investigated. This second phantom, which also is a 3.0cm diameter water sphere, has smaller size.
interior object, a one 0.1mm in diameter and 0.1 mm in length calcium cylinder, as shown in Figure 3-45.

![Figure 3-45 Schematic of Phantom](image)

Simulation results of the DEI images of this phantom are shown in Figure 3-46. The calcium cylinder inside the phantom can be seen on the low angle and high angle side images but not at high clarity. The refraction angle image (DEI image) clearly shows the boundaries of the calcium cylinder, which indicates a small object as small as 0.1mm can easily be identified. Thus, a DEI image can significantly improve image contrast.

![Images of DEI images](image)
3.6 Simulation of Absorbed Dose

MCNP5 code calculation of the dose equivalence was performed for the source using a lead thickness of 0.2, 0.4 and 0.6cm. The MCNP input file is listed in Appendix B-2. The schematic geometry of this simulation is shown in Figure 3-47. The Dose detector, point detector, was placed behind the lead shielding. In Figure 3-48, dose equivalence changes with the applied high voltage on the focusing cup. At -60kV with 0.2cm lead shield, the dose equivalence is around $1 \times 10^{12}$ rem/hr. Comparing this value to the permissible dose limit for general public, $100 \text{mrem/yr} \approx 1.17 \times 10^{-5} \text{rem/hr}$ set by NRC, the obtained dose equivalence is very small. Hence, with 0.2 cm thick lead shielding surrounding the vacuum chamber is efficient enough to block the radiation.
Figure 3-47 Schematic diagram of the shielding geometry for MCNP calculations

Figure 3-48 Dose equivalence versus applied voltage
4 Lab-Based Experiments

The lab-based experimental device was constructed from the filament-target assembly, housed inside of a 6 inch-6 way high vacuum steel cross, and is equipped with filament and high voltage power supplies, air-cooled turbo molecular pump venting to a mechanical pump, vacuum gauges with associated instrumentation, diagnostic ports and a viewing window. A Faraday cup is installed to measure the beam current at various locations to compare to computational modeling. Thermocouples are attached to the target to measure temperature distribution. A schematic of the experimental setup is given in Chapter 3, Figure 3-1.

4.1 Experimental Setup

A photograph of the filament-target assembly on a 6-inch vacuum flange is shown in Figure 4-1, also shown is a photograph as assembled inside the vacuum chamber. Two side supports, fixed on the flange, hold the target pivoting assembly such that the target tilt angle could be adjusted as desired. The same side supports hold the filament cup. The filament cup connection to the high voltage power supply is via a high vacuum high voltage feedthrough, and the filament is separately supplied by a DC current power supply. Thus, in this assembly the filament is on floating potential while the cup is at negative high voltage. The target is connected to ground through the side supports and the vacuum flange. The focusing cup has a 0.35cm u-shaped groove for the filament, which is inside a 0.8cm u-shaped groove for focusing. The filament is made of tungsten and is 2.5cm long. The filament cup details were previously given in Chapter 3, Figure 3-2. The
anode is made of 3.56 cm diameter oxygen-free copper cylinder, with a 2.80 cm diameter thin layer of molybdenum.

Figure 4-1 Photographs of the filament-target assembly
The entire experimental setup is shown in Figure 4-2, showing the assembled experiment and the control rack. The experiment is constructed and assembled on a mobile cart for easy transport as a portable lab-based test unit.

Figure 4-2 Photograph of the lab-based experimental setup

4.2 Measurement of Electron Distribution on the Target

4.2.1 Experimental setup for electron distribution measurements

A Faraday cup was used to measure the electron distribution at the target. In this experiment, the aluminum disc target was used as a mockup to facilitate the motion of the Faraday cup in and out as close as possible to the target surface. The Faraday cup is made
of glass cylinder with a collection wire in the middle. The collection wire is biased positively to collect electrons. A simple schematic of the Faraday cup and measuring circuit is shown in Figure 4-3, in which a power supply is connected to provide biasing potential to the collection wire, and an ammeter is connected in series to measure the collected electron current.

![Figure 4-3 Schematic diagram of Faraday cup](image)

The Faraday cup was assembled and placed inside the vacuum chamber such that it could easily slide in and out to scan the surface of the target for incoming electrons from the filament. Because of the symmetry assumption, the measurements were only taken by sliding the Faraday cup along the vertical direction of the filament, where the distance from the front surface of the faraday up to the front surface of the filament cup is 1.5cm, as shown in Figure 4-4. The Faraday cup is measuring the
current collected by the inner wire, and the current density is given by \( J_e = -en_e v_e \),\
where \( e \) is the unit charge of the electron, \( n_e \) is the electron number density and \( v_e \) is\
the electron velocity (average velocity over a Maxwellian distribution); hence, the\
measured current is a measure of the electron population at point of measurement. In\
this circuit a resistor was connected in series to the collection wire, and a voltmeter\
was connected across the resistor to measure the voltage. Hence, the electron number\
density is given by \( n_e = \frac{(I_e / A_{wire})}{ev_e} = \frac{V}{R A_{wire} ev_e} \), where \( R \) is the value of the resistor, \( V \)\
is the measured voltage across the resistor and \( A_{wire} \) is the area of the wire collecting\
electrons. Thus, the measured voltage is a measure of the electron number density and\
the spatial distribution could be obtained and expressed in terms of the measured\
voltage.

\[ \text{Figure 4-4 Schematic of the electron distribution measurement setup} \]
4.2.2 Electron distribution experimental results

In all experimental measurements, the Faraday cup collection electrode was biased at 60V. The voltage on the filament cup (backing plate) was varied between 0 to 1400V in 200 volt increments.

For each biasing setting on the filament cup, the Faraday cup was moved along the axis of the target (along the filament direction), between –1.5 to 1.5cm. Experimental results are tabulated in Table 4-1, and plotted in Figure 4-5.

**Table 4-1 Faraday cup output voltage (mV)**

<table>
<thead>
<tr>
<th>Faraday cup position (cm)</th>
<th>0</th>
<th>200</th>
<th>400</th>
<th>600</th>
<th>800</th>
<th>1000</th>
<th>1200</th>
<th>1400</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>7.6</td>
<td>18.9</td>
<td>19</td>
<td>25.2</td>
<td>25.2</td>
<td>27.3</td>
<td>35.4</td>
<td>35.4</td>
</tr>
<tr>
<td>1.0</td>
<td>9.1</td>
<td>23.9</td>
<td>25.1</td>
<td>25.4</td>
<td>31.7</td>
<td>35.6</td>
<td>35.6</td>
<td>35.6</td>
</tr>
<tr>
<td>0.5</td>
<td>9.0</td>
<td>21.2</td>
<td>26.1</td>
<td>28.6</td>
<td>38.1</td>
<td>38.1</td>
<td>38.1</td>
<td>41.4</td>
</tr>
<tr>
<td>0.0</td>
<td>12.6</td>
<td>25.7</td>
<td>28.8</td>
<td>40.9</td>
<td>42.7</td>
<td>45.7</td>
<td>49.6</td>
<td>55.8</td>
</tr>
<tr>
<td>-0.5</td>
<td>10.5</td>
<td>29.0</td>
<td>29.0</td>
<td>35.1</td>
<td>42.5</td>
<td>42.5</td>
<td>41.9</td>
<td></td>
</tr>
<tr>
<td>-1.0</td>
<td>9.8</td>
<td>25.2</td>
<td>29.5</td>
<td>32.3</td>
<td>35.1</td>
<td>40.4</td>
<td>42.5</td>
<td></td>
</tr>
<tr>
<td>-1.5</td>
<td>13.9</td>
<td>21.3</td>
<td>23.4</td>
<td>32.3</td>
<td>33.0</td>
<td>32.9</td>
<td>35.8</td>
<td>35.8</td>
</tr>
</tbody>
</table>
As shown in Figure 4-5, the electron distribution at 0V biasing on the filament cup is almost uniform along the length of the filament. Increasing the biasing potential to 400V shows that the distribution is still uniform, within experimental measuring errors. Further increase of biasing potential to -1200 and -1400 volts, it shows higher population of electrons at the center. These results are similar to the computational results obtained for a 7° target tilt angle with the focusing cup biased at −30kV, which show peaking of electron population at the center of the target, as shown in Figure 4-6. Thus, it is clear that the experimental results closely benchmark computational simulation.
Figure 4-6 Electron distribution on the target for the simulation case of the focusing cup biased at -30kV and 7° target tilt angle (left graph), and experimental measurements for the focusing cup biased at -1400V

4.3 Experimental Measurements of Target Temperature Rise

Three thermocouples were attached to the back surface of the aluminum disc target, and connected to thermocouple modules, as shown in Figure 4-8. Temperature rise, for each thermocouple, was monitored as a function of time for up to 45 minutes. Three cases of filament cup biasing potential were investigated, -1.25kV, -1.5kV and -2.5kV.
For the case of $-1.25\text{kV}$ biasing, experimental and computational results are plotted in Figure 4-8, which show good agreement between measured and calculated results. It is also observed that the temperature of the target’s center is higher than that of the edges, which confirms the computational results previously reported in Chapter 3. Increasing the biasing potential to $-1.5\text{kV}$, as shown in Figure 4-9, increases the target temperature with same similar distribution that shows that the temperature of the center is higher than that of the edges.
Figure 4-8 Experimental and computational result for a –1.25kV biasing potential on the filament cup, also shown is the simulation color map of the target temperature.

Figure 4-9 Experimental and computational result for a –1.5kV biasing potential on the filament cup, also shown is the simulation color map of the target temperature.
The case of –2.5kV biasing, as shown in Figure 4-10, is no difference than the –1.25 and the –1.5kV except that the temperature is higher, with the target’s center showing higher temperature increase as compared to the edges. In this case, the simulation results for the temperature at the center are higher than the measured ones, which is due to the fact that the simulation assumed ideal boundary conditions without thermal radiation losses. These results, for all tested cases, are in good agreement with computational results.

Figure 4-10 Experimental and computational result for a –2.5kV biasing potential on the filament cup, also shown is the simulation color map of the target temperature
5 Conclusions and Recommendations

5.1 Conclusions

Computational and experimental studies of the concept of a long line-filament x-ray source for diffraction-enhanced imaging (DEI) and other potential industrial applications have shown the feasibility of using such source to obtain high contrast images. The photon flux of this source design, using a molybdenum target at 3A beam current, 60kV is $3.59 \times 10^{12}$ photons/mm$^2$/sec, which is compatible to synchrotron flux of $1.4 \times 10^{12}$ photons/mm$^2$/sec. For all other window options for the same molybdenum target at 3A beam current, 60kV, the photon flux is $\sim 10^{11}$ photons/mm$^2$/sec, which would require area magnification to achieve the required equivalent synchrotron flux.

Computational studies of the lab-based proof-of-principle setup have been completed. Electron trajectories and electron distribution on the target were computationally simulated using the SIMION code. Results have shown a near uniform distribution of the electrons on the target, which result in the production of a near rectangular area x-ray beam. Target heat loading was modeled in the COMSOL multiphysics code for un-cooled and actively cooled targets. Code results indicate that the target must be actively cooled when operating at a beam current of 3A and an accelerating potential of –60kV (180kW on the target). Several window options were investigated to optimize removal of low-energy bremsstrahlung x-ray spectra. The concept of a thin metallic layer deposited on the glass-viewing window, which could be achieved by plasma deposition techniques or sputter-deposition using cathodic arcs, have shown that the glass
window is dominant in removal of low-energy x-rays. Computationally obtained images of two phantoms, after monochromatizing the x-ray beam and applying the DEI algorithm, have shown enhanced image contrast, a calcium object of 0.1mm could easily be seen on the obtained images.

The x-ray flux generated by this design with a 3A beam current at 60kV using a graphite window is $\sim 1.2 \times 10^{11}$ photons/mm²/sec, which is an order of magnitude less than that of the synchrotron source. Thus, area magnification by a factor of 10 would be needed to achieve $\sim 10^{12}$ photons/mm²/sec.

Calculations of the dose equivalence, surrounding the x-ray generator (outside of the vacuum chamber), have shown that the setup is safe for operation with the use of a 0.2mm thick lead shielding.

Measurements conducted on the lab-based setup, at low accelerating potentials and low beam currents, showed good correlation between experimental results and computational modeling. Thus, computational modeling could be used as a predicting tool for the design of an industrial scaled up device.

5.2 Recommendations

To further validate the imaging quality, a complete DEI setup is recommended to compare actual experimentally obtained DEI images to computationally obtained ones.
A complete DEI setup model should be simulated, which includes the x-ray source and filter, monochromators and Bragg analyzer at their exact position, and the imagine plate (or detector).

Different complex phantom forms, such as tumor-like phantoms, should also be investigated computationally and experimentally (when a DEI setup is in place), and a quantitative measure of image contrast through signal-to-noise analysis.

Investigation of active cooling with circulated coolant fluid (such as liquid nitrogen), including the fluid dynamics of the coolant into the cooling channel.

It is also recommended to investigate the window heat loading due to photon interaction and radioactive heat flux from the target.
6 List of References


[34] R. W. James, “The optical principles of the diffraction of x-rays”, Ox Bow press, 1982


7 Appendices
Appendix A SIMION 7.0 Code Geometry Input Program

1. SIMION code with the target at 0 degree tilted angle

PA_Define(101,101,101, planar, non-mirrored)

Locate(50,50,50,0.5,0,0,0) ; target
{
    Electrode(1)
    {
        Fill
        {
            within
            {
                cylinder(0,0,0,33,33,4)
            }
        }
    }
}

Locate(50,50,37,0.5,0,0,0) ; Backing plate
{
    Electrode(2)
    {
        Fill
        {
            within
            {
                cylinder(0,0,0,32,32,16)
            }
            notin
            {
                Box3D(-32,-8,-6,32,8,6)
            }
            notin
            {
                Box3D(-32,-14,14,32,4,14)
            }
        }
    }
}

Locate(40,50,31,0.5,-90,0,0) ; filament
2. **SIMION code with the target at 15 degree tilted angle**

```
PA_Define(101,101,101, planar, non-mirrored)
Locate(50,50,50,0.5,0,0,15)
{
    Electrode(1)
    {
        Fill
        {
            within
            {
                cylinder(0,0,0,4,0.4,40)
            }
        }
    }
}

Locate(50,50,37,0.5,0,0,0)
{
    Electrode(2)
    {
        Fill
        {
            within
            {
                cylinder(0,0,0,32,32,16)
            }
        }
    }
}
```
notin
{
  Box3D(-32,-8,-6,32,8,6)
}
notin
{
  Box3D(-32,-4,-14,32,4,14)
}
}

Locate(40,50,31,0.5,-90,0,0)
{
  Electrode(3)
  {
    Fill
    {
      within
      {
        cylinder(0,0,0,0.4,0.4,40)
      }
    }
  }
}

104
Appendix B MCNP Code Input Files

1. X-ray spectrum simulation for different targets at different accelerating potentials

Option 0.001mm Rh and 1.778mm glass window(SiO2), Mo target, 30kV

C cell card

1 1 -8.92 -1 10 -11
2 2 -10.2 (1 :-10 :11 )-1 9 -10 $ Mo target
3 3 -7.874 (1 :-9 :11 )-4 -5 6
4 0 -2 20 -12 #1 #2 #3
5 3 -7.874 (2 :-8 :12 )-3 8 -12
6 3 -7.874 (3 :-8 :12 )-17 3 -12 19
7 3 -7.874 (17 :-3 :12 :-19 )-17 12 -13
8 3 -7.874 (3 :-8 :12 )-17 3 8 -18
9 4 -3.49 -2 -7 8 $ glass window
10 5 -0.00129 -14 15 -16 #1 #2 #3 #4 #5 #6 #7 #8 #9 #12
11 0 (14 :-15 :16 )
12 6 -12.4 -2 7 -20 $ Rh window layer

C surface card

1 1 cz 1.74625
2 cz 7.62
3 cz 7.9248
4 cy 1.5875
5 py -2.5
6 py -5.4
7 pz -16.491 $ 0.1778cm Glass window
8 pz -16.6688 $ with surface 7
9 1 pz -0.1
10 1 pz 0
11 1 pz 5.715 $ target length
12 pz 16.6688
13 pz 18.8913 $ half inch
14 cz 12
15 pz -20
16 pz 20
17 cz 10.16
18 pz -14.4463
19 pz 14.4463
20 pz -16.4909 $ 0.0001cm Rh layer

tr1 0 0 0 1 0 0 0 0.3826 -0.9239 0 0.9239 0.3826
mode p e
m1 29000 1 $MAT
<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>m2</td>
<td>42000</td>
<td>1 $Mo target MAT</td>
</tr>
<tr>
<td>m3</td>
<td>26000</td>
<td>1 $SMAT</td>
</tr>
<tr>
<td>m4</td>
<td>14000</td>
<td>0.333 $SMAT</td>
</tr>
<tr>
<td></td>
<td>8000</td>
<td>0.667</td>
</tr>
<tr>
<td>m5</td>
<td>7000</td>
<td>0.78 $SMAT</td>
</tr>
<tr>
<td></td>
<td>8000</td>
<td>0.22</td>
</tr>
<tr>
<td>m6</td>
<td>45000</td>
<td>1 $ Rh window</td>
</tr>
</tbody>
</table>

imp:p 1 9r 0 1 $, 1, 12

imp:e 1 9r 0 1 $1, 12

sdef x=D1 y=-2.5 z=D2 erg=0.03 par=3 dir=1 vec=0 1 0

sp1 -41 .22 0

sp2 -41 .12 0
e0 1.0e-4 999I 0.1 $Ka2 0.01737 Ka1 0.01748 Kb1 0.01961

f2:p 7 $surface flux 7

sd2 1.82322E+02

f12:p 8 $surface flux 8

sd12 1.82322E+02

f22:p 15 $surface flux 15

sd22 1.82322E+02

f32:p 20 $surface flux 20

sd32 1.82322E+02

nps 100000000

prdmp 10000000 10000000 1 1

print 10 50 110

Figure 7-1 View of MCNP simulation geometry
2. *Dose calculations for different target at different applied high-potential*

Option 1.778mm glass window(SiO2)

**c cell card**

1 1 -8.92  -1 10 -11  
2 2 -10.208 (1 :-10 :11 )-1 9 -10  
3 3 -7.874 (1 :-9 :11 )-4 -5 6  
4 0 -2 7 -12  #1 #2 #3  
5 3 -7.874 (2 :-8 :12 )-3 8 -12  
6 3 -7.874 (3 :-8 :12 )-17 3 -12 19  
7 3 -7.874 (17 :-3 :12 :-19 )-17 12 -13  
8 3 -7.874 (3 :-8 :12 )-17 3 8 -18  
9 4 -3.49 -2 -7 8 $glass window  
10 5 -0.00129 -14 15 -16  #1 #2 #3 #4 #5 #6 #7 #8 #9  
11 0 (14 :-15 :16 )

**c surface card**

1 1 cz 1.74625  
2 cz 7.62  
3 cz 7.9248  
4 cy 1.5875  
5 py -2.5  
6 py -5.4  
7 pz -16.491 $0.1778cm Glass window  
8 pz -16.6688 $with surface 7  
9 1 pz -0.1  
10 1 pz 0  
11 1 pz 5.715 $Target length  
12 pz 16.6688  
13 pz 18.8913 $Half inch  
14 cz 13  
15 pz -17  
16 pz 20  
17 cz 10.16  
18 pz -14.4463  
19 pz 14.4463  

tr1 0 0 0 1 0 0 0 0.3826 -0.9239 0 0.9239 0.3826  
mode p e  
m1 29000. 1 $MAT  
m2 42000. 1 $MAT  
m3 26000. 1 $MAT  
m4 14000. 0.333 $MAT  
8000. 0.667  
m5 7000. 0.78 $MAT
imp:p 1 10r $ 1, 11
imp:e 1 10r $ 1, 11
sdef x=D2 y=-2.5 z=D1 erg=0.01 par=3 dir=1 vec=0 1 0
sp1 -41 0.288 0 $Function-dependent electron source distribution
sp2 -41 0.706 0
f5:p 0 0 -17 +2 $Flux at a point detector (0 0 -16)
de5 lin 0.01 0.08 $Dose calculation for both tallies
df5 lin 2.78e-6 1.20e-7 $Ref. MCNP manual Table H.2
nps 300000
prdmp 300000 300000 1 1
print 10 50 110

3. DEI imaging simulation

Option 0.001mm Mo and 1.778mm glass window (SiO2)
c cell card
1 1 -8.92 -1 10 -11
2 2 -10.208 (1 :-10 :11 )-1 9 -10
3 3 -7.874 (1 :-9 :11 )-4 -5 6
4 0 -2 20 -12 #1 #2 #3
5 3 -7.874 (2 :-8 :12 )-3 8 -10
6 3 -7.874 (3 :-8 :12 )-17 3 -12 19
7 3 -7.874 (17 :-3 :12 :19 )-17 12 -13
8 3 -7.874 (3 :-8 :12 )-17 3 8 -18
9 4 -3.49 -2 -7 8 $glass window
10 5 -0.00129 -14 15 -16 #1 #2 #3 #4 #5 #6 #7 #8 #9 #12
11 0 (14 :-15 :16 )
12 2 -10.208 -2 7 -20 $mo layer
c surface card
1 1 cz 1.74625
2 cz 7.62
3 cz 7.9248
4 cy 1.5875
5 py -2.5
6 py -5.4
7 pz -16.491 $0.1778cm Glass window
8 pz -16.6688 $with surface 7
9 1 pz -0.1
10 1 pz 0
11 1 pz 5.715 $target length
12 pz 16.6688
13 pz 18.8913 $half inch
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<td></td>
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</tr>
<tr>
<td></td>
<td>20 pz</td>
<td>-16.4909</td>
</tr>
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</table>

$0.0001$ cm mo layer

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</tr>
<tr>
<td></td>
<td>m2</td>
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<td></td>
<td>m3</td>
<td>26000 1 SMAT</td>
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<tr>
<td></td>
<td>m4</td>
<td>14000 0.333 SMAT 8000 0.667</td>
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<td>m5</td>
<td>7000 0.78 SMAT 8000 0.22</td>
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<td>1 9r 0 1 $1,12</td>
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<td>imp:e</td>
<td>1 9r 0 1 $1,12</td>
</tr>
<tr>
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<td>sdef x=D1 y=-2.5 z=D2 erg=0.06 par=3 dir=1 vec=0 1 0</td>
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<td></td>
<td>sp1</td>
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</tr>
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<td></td>
<td>sp2</td>
<td>-41 .12 0</td>
</tr>
<tr>
<td></td>
<td>e0</td>
<td>1.0e-4 999I 0.1 $Ka2 0.01737 Ka1 0.01748 Kb1 0.01961</td>
</tr>
<tr>
<td></td>
<td>f2:p</td>
<td>7 $surface flux 7</td>
</tr>
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<td>1.82322E+02</td>
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<td></td>
<td>f22:p</td>
<td>15 $surface flux 15</td>
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</table>
Appendix C  X-Ray Spectrum

Figure 7-2 X-ray spectrum with Mo target, 0.001mm Rh + Glass window, -60kV

Figure 7-3 X-ray spectrum with Mo target, 0.001mm Mo + Glass window, -60kV
Figure 7-4 X-ray spectrum with Mo target, 0.001mm Al +Glass window, -60kV

Figure 7-5 X-ray spectrum with Mo target, 0.001mm Be +Glass window, -60kV
Figure 7-6 X-ray spectrum with Mo target, Glass window, -60kV

Figure 7-7 X-ray spectrum with Mo target, graphite window, -60kV
Figure 7-8 X-ray spectrum with Mo target, 0.01mm Rh + Glass window, -60kV

Figure 7-9 X-ray spectrum with Mo target, 0.01mm Mo + Glass window, -60kV
Figure 7-10 X-ray spectrum with Mo target, 0.01mm Al + Glass window, -60kV

Figure 7-11 X-ray spectrum with Mo target, 0.01mm Be + Glass window, -60kV
Figure 7-12 X-ray spectrum with Rh target, 0.001mm Rh + Glass window, -30kV

Figure 7-13 X-ray spectrum with Rh target, 0.001mm Mo + Glass window, -30kV
Figure 7-14 X-ray spectrum with Rh target, 0.001mm Al + Glass window, -30kV

Figure 7-15 X-ray spectrum with Rh target, 0.001mm Be + Glass window, -30kV
Figure 7-16 X-ray spectrum with Rh target, Glass window, -30kV

Figure 7-17 X-ray spectrum with Rh target, graphite window, -30kV
Figure 7-18 X-ray spectrum with Rh target, 0.01mm Rh + Glass window, -30kV

Figure 7-19 X-ray spectrum with Rh target, 0.01mm Mo + Glass window, -30kV
Figure 7-20 X-ray spectrum with Rh target, 0.01 mm Al + Glass window, -30kV

Figure 7-21 X-ray spectrum with Rh target, 0.01 mm Be + Glass window, -30kV
Figure 7-22 X-ray spectrum with Rh target, 0.001mm Rh + Glass window, -60kV

Figure 7-23 X-ray spectrum with Rh target, 0.001mm Mo + Glass window, -60kV
Figure 7-24 X-ray spectrum with Rh target, 0.001mm Al + Glass window, -60kV

Figure 7-25 X-ray spectrum with Rh target, 0.001mm Be + Glass window, -60kV
Figure 7-26 X-ray spectrum with Rh target, Glass window, -60kV

Figure 7-27 X-ray spectrum with Rh target, graphite window, -60kV
Figure 7-28 X-ray spectrum with Rh target, 0.01mm Rh + Glass window, -60kV

Figure 7-29 X-ray spectrum with Rh target, 0.01mm Mo + Glass window, -60kV
Figure 7-30 X-ray spectrum with Rh target, 0.01mm Al +Glass window, -60kV

Figure 7-31 X-ray spectrum with Rh target, 0.01mm Be +Glass window, -60kV
Figure 7-32 X-ray spectrum with W target, 0.001mm Rh +Glass window, -100kV

Figure 7-33 X-ray spectrum with W target, 0.001mm Mo +Glass window, -100kV
Figure 7-34 X-ray spectrum with W target, 0.001mm Al + Glass window, -100kV

Figure 7-35 X-ray spectrum with W target, 0.001mm Be + Glass window, -100kV
Figure 7-36 X-ray spectrum with W target, Glass window, -100kV

Figure 7-37 X-ray spectrum with W target, graphite window, -100kV
Figure 7-38 X-ray spectrum with W target, 0.01mm Rh +Glass window, -100kV

Figure 7-39 X-ray spectrum with W target, 0.01mm Mo +Glass window, -100kV
Figure 7-40 X-ray spectrum with W target, 0.01mm Al + Glass window, -100kV

Figure 7-41 X-ray spectrum with W target, 0.01mm Be + Glass window, -100kV
Appendix D Estimation of Operation Time

*(Originally calculated by Dean Chapman for a 10kW “75kV, 130mA” x-ray source)*

Due to the fact that the $k_{\alpha 1}$ characteristic x-ray is used in this design, the required flux will be estimated at 18keV, and a 5.0 milli-Rads approximate dose delivery to the detector. The number of photons striking the detector will be estimated from this dose limit, thus the dose in terms of photons per unit area is given by:

$$D(\text{Rad}) = \frac{N(\text{photons} / \text{cm}^2)E(eV / \text{photon})\frac{\mu_{\text{tot}}(\text{cm}^{-1})}{\rho}(1 - e^{-\mu_{\text{tot}}(\text{cm}^{-1})/\rho})}{\rho(\text{gm/cm}^2)v(\text{cm}^3))10^7(\text{ergs/gm})A(\text{cm}^2)}$$

Which in the limit of a thin object can be converted to an entry dose or surface dose $\mu_{\text{tot}}<<1$. At 18keV the values of $\frac{\mu_{\text{tot}}}{\rho}$ and $\frac{\mu_{\text{ea}}}{\rho}$ are 1.01cm$^2$ / gm and 0.73cm$^2$ / gm, respectively. Hence the above equation reduces to:

$$D_{\text{skin}}(\text{Rad}) = N(\text{photons} / \text{cm}^2)E(eV / \text{photon})\frac{\mu_{\text{ea}}(\text{cm}^2 / \text{gm})1.6 \times 10^{-14}(\text{Rad gm/eV})}{\rho}$$

From which the photon flux is:

$$N(\text{photons} / \text{cm}^2) = \frac{D_{\text{skin}}(\text{Rad})}{E(eV / \text{photon})\frac{\mu_{\text{ea}}(\text{cm}^2 / \text{gm})1.6 \times 10^{-14}(\text{rad gm/eV})}{\rho}}$$

Using the 5 milli-Rads dose value and the energy absorption coefficient for water “given at 18keV”, a detector flux could be obtained:

$$N_{\text{Detector}}^{18\text{keV}} = \frac{5 \times 10^{-3}\text{rad}}{18000eV / \text{ph} \times 0.73\text{cm}^2 / \text{gm} \times 1.6 \times 10^{-14}\text{Rad gm/eV}} = 2.7 \times 10^7 \text{ ph / cm}^2$$

$$= 2.7 \times 10^5 \text{ ph / mm}^2$$

Assuming a detector pixel size of 50 microns on a side one can obtain the photon count into each pixel as:

$$N_{\text{Detector}}^{18\text{keV}} = 2.7 \times 10^7 \text{ photons / cm}^2 \times (0.005\text{cm})^2 = 675 \text{ photons / 50 \mu m square pixel}$$

Therefore, to obtain a good conventional mammogram there will be a need for 1000 photons / 50 micron square pixels.
Assuming the x-rays traverses 5cm of tissue (water), and employing the exponential attenuation law, one can obtain the incident flux to the object at the energy of 18keV:

\[ N_{\text{Surface}}^{18\text{keV}} = \frac{1000 \text{photons/} \text{pixel}}{e^{-\mu t}} = \frac{1000 \text{photons/} \text{pixel}}{6.4 \times 10^{-3}} = 1.6 \times 10^5 \text{photons/}50\mu\text{msqpixel} \]

Most x-ray tubes, thermionic type, radiate more-or-less uniformly into all solid angles, and thus it is required to calculate the flux based on the solid angle subtended by the detector and the x-ray crystal optics. When a perfect crystal is used, the peak reflectivity for the reflection will be very close to unity, therefore, the integrated reflectivity will be close to the intrinsic reflection width (Dean Chapman, 2001). The emission line energy widths will be comparable to the bandwidth set by a perfect crystal. The crystal will not restrict x-rays in energy other than to select one of the emission lines; the K_{α1} in this case. Therefore, the crystal will appear to be an angular slit in the direction perpendicular to the lattice planes (Bragg-normal) and will not define the x-rays in the direction parallel to the lattice planes (Bragg-parallel). The angular acceptance in the Bragg-normal direction is the Darwin width. For a Si (333) crystal and 18keV, the Darwin width is 2.9 x 10^{-6} radians.

The crystal does not set the angular acceptance for the Bragg-parallel direction, but by the detector or resolution required at the object. Assuming the object is set at 1.0m from the x-ray source and requires a 50micron spatial resolution at that location, and then the photon flux at the Bragg-parallel acceptance angle of 50microradians is then given by:

\[ N_{\text{Required}}^{18\text{keV}} = \frac{1.6 \times 10^5 \text{photons/} \text{pixel}}{2.9 \times 10^{-6} \text{radians} \times 50 \times 10^{-6} \text{radians/} \text{pixel}} = 1.1 \times 10^{15} \text{photons/steradian} \]

For the molybdenum target of this line source design operating at 180kW of power (3A beam current at 60kV) the estimated flux emitted into the K_{α1} (17.478keV) is:

\[ n_{\text{Source}}^{\text{MoK}_{α1}} = 1.7 \times 10^{15} \text{photons/steradian/sec} \]

If to assume performing DEI in which we detune the analyzer from the peak position by a factor of two in transmitted intensity and we acquire two exposures (one on each side of the rocking curve); the flux requirements will increase by a factor of four. Because the system assumes a single monochromator and analyzer crystal, then an imaging line beam would be created and scanning the object is necessary.

If scanning a 150mm object with a beam thickness of 3.2mm to obtain a DEI image then the total number of scans required would be 150mm/3.2mm = 47 scans. Using the photon flux at the Bragg-parallel acceptance angle of 50microradians, 1.1x10^{15} photons/steradian, the flux emitted into the K_{α1} (17.478keV) from the molybdenum target (1.7x10^{15} photons/steradian/sec) and the required number of scans, the time required to obtain a DEI image would be:
\[
T = \frac{1.1 \times 10^{15} \text{ photons/steradian}}{1.7 \times 10^3 \text{ photons/steradian/sec}} \times 2 \times 2 \times 47 = 121.65 \text{ sec} \approx 2.03 \text{ minutes}
\]

This operation time, to obtain a DEI image, is quite fast than that of conventional mammography.