A Novel Metrology Standard for Synchrotron Produced Monochromatic X-ray Beams

by

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Abstract

Purpose: X-ray beams produced using synchrotrons have unique properties that are of interest to radiotherapy investigations and the characterization of radiation detectors. To facilitate the use of synchrotron produced photons in such investigations, this project aims to determine the absorbed dose to water at depth for synchrotron-produced monochromatic x-ray beams with a standard uncertainty less than 1 %, significantly lower than current methods.

Methods: The absorbed dose to water at a depth of 2 cm, $D_{w, 2cm}$, was evaluated using a purpose built novel aluminum calorimeter design. Finite element modeling and radiation transport simulations were performed to refine the design, calculate correction factors, and assess influence quantities. Two iterations of the design were constructed to test calorimeter operation and a comparison of the quantity air kerma, using a secondary microDiamond detector, was performed.

Results: The combined standard uncertainty in the determination of absorbed dose to water was estimated to be 0.89 %, and was found to be constant for monochromatic energies investigated (80 keV to 140 keV). No dependence on calorimeter design was observed and the comparison with the microDiamond detector showed agreement in the determination of air kerma rate at the 1.5 % level, providing confidence in the new calorimeter standard.

Conclusions: This new calorimeter has been shown to accurately determine absorbed dose to water in synchrotron-produced x-ray beams with a substantially lower uncertainty compared to current methods. Routine operation has also been demonstrated, providing a new high-accuracy dosimetric tool for users of synchrotron beams, initially in Canada but potentially at sites worldwide.
Acknowledgements

I have had the privilege to work with my supervisor for more than a decade and during that time I have learnt an immeasurable amount and was given the opportunity to work on many exciting projects. There was never a time when he was not available to give valuable advice, for which I am truly grateful. Being given the opportunity and freedom to pursue this novel thesis has been exciting even considering the challenges of traveling during the pandemic!

Jean Dessureault has been integral to the success of this project, providing advice and regularly going above and beyond to ensure the designs were precisely built. It has been a pleasure to work on this project with him. I would also like to thank David Marchington, James Renaud, Hong Shen, Bryan Muir, Ernesto Maineegra-Hing and Claudiu Cojocaru for readily giving their time to help at different stages of this project. I have spent more than a decade at the Ionizing Radiation Standards group and will surely struggle to find another group of friends more dedicated to their craft, while always making everyone feel at home. Many members of the group have also contributed to the success of this project.

Finally, I would like to thank my wife, Leanna Haidar, who has given her time and support without fail throughout the course of my PhD. For all the times when things seemed hopeless, I could always count on her to show me the light at the end of the tunnel!
Statement of Originality

This thesis summarizes the author’s research over the course of his doctoral studies. The work has been published in the peer-reviewed papers and conference presentations listed below. This project was completed under the supervision of Dr. Malcolm McEwen, where he has provided guidance throughout the project and provided comments on the published thesis and peer-reviewed papers. The author performed all of the measurements, design, computational work, analysis of the results and prepared the manuscript.

Peer-reviewed papers


Conference abstracts (*indicates presenting author)


Canadian Organization of Medical Physicists (COMP) annual scientific meeting.


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Chapter 1

Introduction

Cancer is the leading cause of death in Canada, with an estimated 40 % of Canadians expected to be diagnosed with the disease in their lifetime [1]. More than 50 % of solid cancers are treated with radiotherapy [2]. This has been the main motivation to explore new treatment modalities to reduce patient mortality. The ultimate goal of radiation therapy is the killing of cancerous cells while sparing normal tissues. To achieve this, radiation therapy treatments have relied on increasingly complex conformal treatments that avoid irradiating non-cancerous tissues and various temporal fractionation regimes.

Recently the FLASH effect has proved to be a promising area of research [3]. By delivering doses to tissues orders of magnitude higher than conventional treatments, 40 Gy/s vs 5 Gy/min, normal tissue sparing is observed while preserving the rate of cancerous cell kill. The mechanism behind FLASH radiotherapy is not fully understood. An enhancement of the FLASH effect has been observed when dose is deposited in a spatially fractionated way, referred to as micro-beam radiotherapy or MRT [4].

Photon sources are indirectly ionizing and deposit their energy through secondary
charged particles, electrons, liberated in the media that they traverse. Secondary charged particles can have large ranges and to preserve the spatial fractionation required for MRT the use of kV x-rays is required, where the low energy secondary charged particles have sufficiently short ranges.

The large dose rates required to study the FLASH effect are impractical for kV x-ray tubes, the most common type of x-ray source. Synchrotron produced x-rays have dose rates orders of magnitude greater. Any quantitative investigation of MRT requires accurate and precise dosimetry.

The ability of synchrotron sources to produce high dose rate monochromatic beams can also serve to characterize the energy response of different detectors. Many detectors suffer from large changes in output as a function of energy in the keV range. Currently this is assessed using x-ray tubes with complex energy spectra. The ability to quantify detector response as a function of a single energy as opposed to a spectrum, will allow a detector’s energy response to be more precisely characterized and increase the usability of many detectors over a larger energy range. This becomes possible in a monochromatic synchrotron beam with a known dose rate.

Synchrotrons provide unique measurement challenges that increase the uncertainty on using conventional x-ray detectors, such as an ion chamber. A purpose built detector to address these unique measurement challenges will allow more quantitative research using synchrotron sources to take place.

A first step in performing quantitative research on a synchrotron beamline involves defining the dose rate for a broad beam [5–8] i.e without the collimation necessary to produce an MRT field. This condition readily extends to detector characterization investigations as well. The goal of this work is to develop a purpose built detector to determine the absorbed dose rate to water due to a monochromatic synchrotron beam,
and to serve as a first step towards providing an accurate and traceable metrology primary standard for synchrotron produced x-rays.

A primary standard in this context aims to determine the absorbed dose independently from any other radiation based measurement. Primary standards are expected to determine the quantity of interest with the lowest possible uncertainty. A primary standard is then typically used to calibrate secondary detectors for routine use and in doing so establish traceability between the primary standard and routine measurements performed with a calibrated detector. Standards are developed and maintained by National Metrology Institutes, NMIs, with the National Research Council Canada, NRC, being the Canadian NMI.

The thesis is laid out as follows. A formalism to discuss radiation detector properties is outlined in chapter 2, in addition to a discussion of common kV x-ray detectors. Chapter 2 concludes with a review of the literature pertaining to synchrotron dosimetry. Chapter 3 outlines the detector design requirements and the assessment of a novel calorimeter design to meet them, using a series of radiation transport and thermal simulations. The chapter concludes with an overview of the procedure used to construct a prototype of this design. Chapter 4 presents a proof of principle study using the first calorimeter prototype and outlines necessary improvements to the design. Chapter 5 describes changes made to the original design and a series of experiments to assess the performance of the second prototype. The chapter concludes with a preliminary validation of the calorimeter by comparing the air-kerma measured using the calorimeter with that determined using another detector in the synchrotron beam. The thesis concludes in chapter 6 with the determination of the ultimate quantity of interest, absorbed dose to water, and the calibration of a secondary detector for routine use.
The calorimeter vessel was built, based on the authors detailed designs, by NRC Design and Fabrication Services. Assembly and construction of the remaining components of the calorimeter was performed by Jean Dessureault, who also provided valuable input in making the build practical. The author was responsible for all the design, simulation, measurement and analysis of the results presented in this thesis.
Chapter 2

Radiation Dosimeter Characteristics

2.1 Dosimetry Formalism

When investigating the efficacy of a dosimeter for a particular application, a number of characteristics have to be assessed. Consequently, this section aims to describe and define the terminology used throughout this work. The notation used is consistent with that introduced by Rogers et al [9].

The absorbed dose at a point, the energy deposited per unit mass, in an irradiated medium is a function of the radiation field irradiating it. A complete description of the field requires knowledge of the particle types, their energies and their spatial distributions [10]. The concept of particle fluence \( \phi \) is introduced, defined by the International Commission on Radiation Units and Measurements as, "the quotient of \( dN \) by \( da \). Where \( dN \) is the number of particles incident on a sphere of cross-sectional area \( da \)." [11], equation 2.1.
The particle radiance differential in energy, equation \(2.2\), defines the energy fluence of particles, \(\phi_E = \frac{d\phi}{dE}\), propagating within a solid angle \(\Omega\) as a function of position \(\vec{r}\).

\[
\phi_E(\vec{r}) = \frac{d\phi}{d\Omega dE}
\]  

The particle fluence differential in energy and angular distribution as a function of position within the field provides the necessary information to fully describe an irradiating field. Obtaining a complete description of the field in this way is often impractical for polychromatic beams \([10, 12–14]\), such as the spectrum depicted in figure 2.1. In practice radiation quality is characterized using different beam quality specifiers that provide an acceptable approximation of the field, while allowing accurate dosimetry \([15–17]\). For kV x-ray beams, a combination of half-value layer, tube voltage (kV\(_p\)) and added filtration is typically used to specify the beam quality. The half-value layer is defined as the thickness of material, usually aluminum or copper, required to reduce the intensity of the beam by 50\% \([17]\). In the case of a monochromatic beam the energy and solid angle fluence distribution would uniquely define the field.

Ideally, a dosimeter attempts to realize the absorbed dose to some medium, denoted by the subscript med, using equation 2.3 in the absence of the dosimeter. The dosimeter reading is denoted by \(M_{det}\), in response to a beam of quality Q. The dosimeter reading is any quantifiable response to the absorbed dose in the medium, examples include; the charge collected by an ion chamber, or the change in optical absorbance of film. \(N_{D,med}\) is a calibration coefficient to convert the dosimeter reading to an absorbed dose reading, a function of the beam quality and the intrinsic properties.
Figure 2.1: A Monte Carlo calculated energy spectrum of a 150 kVp X-ray beam, filtered with 4.0 mm of Aluminum and 2.5 mm of Tin, to illustrate a typical kV x-ray tube generated spectrum. The spectrum was simulated at 1 m from the x-ray source to allow for the attenuation of lower energy photons in air. The beam would be typically described as having a beam quality of 150 kVp and a 2.42 mm copper half-value layer.

of the detector [9]. For medical dosimetry applications the medium is most often water, used as an analogue to human soft tissue.

\[
D_{med} = M_{det}(Q)N_{D,med}(Q) \tag{2.3}
\]

A dosimeter reading is unlikely to be only dependent on the beam quality. Most dosimeters have to be corrected for changes in response to ambient environmental conditions. Typically, a dosimeter’s sensitivity to temperature, pressure and humidity must be evaluated. In the case of an ion chamber, whose purpose is to collect the charge liberated by incident ionizing radiation in an air cavity, the mass of air within the fixed volume cavity would change in response to changes in ambient temperature and pressure, resulting in a different charge reading for the same radiation field [16]. In
the case of a chemical dosimeter, where the reading is based on the result of a radiation sensitive reaction, the rate of reaction can be temperature dependent requiring an additional correction. An environmental correction is denoted by $k_{env}(T, P, H)$, to correct the raw dosimeter reading to a reference temperature, pressure and humidity.

The dosimeter reading may additionally depend on the dose rate being measured. In the case of ion chambers, charge recombination effects are dose rate dependent and have to be evaluated [16, 18]. For chemical dosimeters, recombination of reaction products can occur at higher dose rates as well [19]. To correct the raw dosimeter reading for any dose rate dependence, the following correction is introduced, $k_{dr}(\dot{D})$.

A final consideration, for some detectors is the intrinsic linearity of the dosimeter. For most dosimeters the detector response is linear with respect to the absorbed dose, the ratio of dosimeter reading to absorbed dose is expected to be a constant. Some chemical dosimeters, such as radiochromic film, exhibit a non-linear response to the absorbed dose [20]. To correct for non-linearities in detector response, $k_{l}(M(D))$ is introduced as a function of the absorbed dose. Alternatively, if the absorbed dose range over which the dosimeter is linear is specified, $k_{l}(M(D))$ can be taken as unity.

The fully corrected dosimeter reading can then be represented as:

$$M_{det}(Q) = k_{l}(M(D))k_{dr}(\dot{D})k_{env}(T, P, H)M_{raw}(Q)$$

Where, $M_{raw}(Q)$ denotes the raw uncorrected dosimeter reading.

Knowledge of the energy dependence of a dosimeter is essential to fully characterize it. The energy dependence is included in $N_{D,med}$ in equation 2.3. Following the notation of Rogers et al. the energy dependence can be considered to be due to the detector’s intrinsic energy dependence and absorbed dose energy dependence. The intrinsic energy dependence, $k_{bq}(Q)$, relates the change in dosimeter reading per unit dose,
deposited in the sensitive volume of the detector for a given beam quality and is defined as:

\[ k_{\text{q}}(Q) = \frac{D_{\text{det}}(Q)}{M_{\text{det}}(Q)} \]  

(2.5)

Fricke dosimetry [19] provides an intuitive example of the importance of characterizing the intrinsic energy dependence of a dosimeter. The basis of Fricke is that it relates the dose to the number of ferric ions produced in an aqueous solution. The number of ferric ions created per unit dose absorbed by the Fricke solution denotes the radiation chemical yield, the dosimeter’s intrinsic energy dependence in this formalism [19]. The number of ferric ions produced per unit dose is a function of the beam quality, with the number of ferric ions produced in a 250 kVp x-ray beam being on the order of 3 % lower than the number produced in a Co-60 beam [19, 21]. This would directly translate to a 3 % error in the dose evaluated using a Fricke dosimeter, calibrated using a Co-60 beam but used to perform measurements in a 250 kVp beam [21]. The intrinsic energy dependence is a function of the measured dosimeter response and consequently cannot be determined without measurement.

A detector’s absorbed dose energy dependence, \( f(Q) \), relates the absorbed dose to the detector medium to the absorbed dose to the medium in the absence of the detector.

\[ f(Q) = \frac{D_{\text{med}}(Q)}{D_{\text{det}}(Q)} \]  

(2.6)

In the case of the Fricke chemical dosimeter, a good approximation for the absorbed dose energy dependence would be a ratio of mass energy absorption coefficients of Fricke and the medium of interest [22]. The ratio of mass energy absorption coefficients
accounts for the difference in energy deposition between the medium and the Fricke solution. The perturbation of the fluence in the medium due to the presence of the detector, appearing as additional scatter and attenuation affects, also contributes to the absorbed dose energy dependence. For the most rigorous calculation of the absorbed dose energy dependence a beam transport simulation is necessary with an accurate model of the dosimeter [9].

As a result equation 2.3 can be re-written as:

\[
D_{med}(Q) = M_{det}(Q)N_{D,med}(Q) = M_{det}(Q)f(Q)k_{bq}(Q)
\] (2.7)

All dosimeters average the dose over a sensitive detection volume, although that volume can be negligibly small for some dosimeters. However, in situations where the sensitive volume of the detector is no longer negligible with respect to the radiation field size a detector’s response can change significantly [23, 24]. Volume averaging is a concern for small beam applications such as stereotactic radiotherapy [23, 24]. Volume averaging is often denoted as a separate correction \(k_{vol}\), indicating that it needs to be explicitly determined.

In conclusion the dose to a medium of interest can be evaluated as a function of a dosimeter’s raw reading for a beam quality, \(Q\), as:

\[
D_{med} = f(Q)k_{bq}(Q)k_{vol}(Q)k_{i}(M(D))k_{dr}(\dot{D})k_{env}(T, P, H)M_{raw}(Q)
\] (2.8)
2.2 Kilo-Voltage X-ray Detectors

2.2.1 Ionometry

Ion chambers are the most commonly used dosimeter for kV x-ray beams, and form the basis of the AAPM TG-61 dosimetry protocol used throughout North America [17]. Ion chambers measure the number of ion pairs created by ionizing radiation interacting in an air cavity [25, 26]. A high voltage, on the order of 300 V, is applied across the air cavity and the charge liberated measured using an electrometer [26]. Figure 2.2 shows a schematic of a typical cylindrical ion chamber, along with the collecting volume and electrode. To determine absorbed dose in kV x-rays, ion chambers must first be calibrated, usually in terms of air-kerma [17]. Air-kerma is defined as the energy imparted by uncharged particles, photons in the case of kV x-rays, to charged particles per unit mass of air [10]. Multiplying the charge collected by the air-kerma calibration factor $N_k$, provides the air-kerma at the measurement position. To convert air-kerma to dose in a medium the result must be multiplied by a ratio of mass energy absorption coefficients averaged over the entire beam fluence weighted energy spectrum, equation 2.9 [17].

$$D_{w,2cm} = MN_k P_Q \left( \frac{\mu_{en}}{\rho} \right)_{water} \frac{\mu_{en}}{\rho}_{air}$$  \hspace{1cm} (2.9)

The TG-61 protocol requires measurements at a depth of 2 cm in a water phantom, for the in phantom method discussed for 100 - 300 kVp beams [17]. $P_Q$, in equation 2.9, corrects the ion chamber reading for the presence of the air cavity in the phantom, ensuring the dose is provided at a depth of 2 cm. The point of measurement is set by the position of a cylindrical ion chamber’s central axis, the electrode in figure 2.2 [17].
A depth of 2 cm is meant to ensure a large enough charge is measured and full build up of secondary electrons is achieved. Secondary electrons are those electrons released through ionization of the medium or chamber wall by the x-ray photons. Full build-up implies that the change in the electron fluence with depth, and consequently the charge collected by the chamber, is chiefly due to the attenuation of the ionizing photons and not the number of electrons generated upstream. A depth of 2 cm additionally ensures that the photon beam has not been significantly attenuated once full buildup is achieved, resulting in a measurable signal.

One of the main advantages of ion chambers is that the intrinsic energy dependence is not a function of beam quality, since the energy needed to create an ion pair in air is considered to be constant with a value of 33.97 $J \, C^{-1}$ [26, 27]. However, ion chambers exhibit an absorbed dose energy dependence that is a function of beam quality and $P_Q$. In equation 2.9 this is accounted for by both $N_K$ and $[\frac{\mu_{en}}{\rho}]_{water}$. For ion chambers the absorbed dose energy dependence depends on the chamber dimensions, wall material and electrode material [26]. Polarity effects, the difference in charge collected when the polarity of the supplied voltage is inverted, can also be viewed to be a function of beam quality. Polarity effects can be attributed to charges produced outside the chamber collecting volume, charge production in the central electrode and electric

**Figure 2.2:** Left: An Exradin A1SL chamber (Standard Imaging, Middleton, WI) Right: Chamber schematic with the collecting volume, 0.053 cm$^3$, shaded.
field distortions within the chamber [26, 28]. $P_{pol}$ is calculated such that $P_{pol}M$ gives the averaged chamber response, removing the polarity dependence which is typically on the order of 0.3 % [16, 17].

The ion chamber reading must be corrected for the remaining influence quantities outlined in equation 2.8. $k_{env}(T, P, H)$ accounts for the changes in the mass of air present in the fixed volume cavity, chambers are corrected relative to room temperature, $22 \, ^\circ\text{C}$, and pressure 101.33 kPa. Additionally, ion chambers should be operated between 20 - 80 % humidity when measurements are performed in air. The presence of water vapor in the air would decrease the mean energy required to create an ion pair, whilst increasing the electron stopping power in the air cavity, fortunately this results in a 0.15 % effect and is considered constant between 20 - 80 % humidity [29].

Ion chamber response can potentially vary as a function of dose rate. An ion chamber’s dose rate dependence is a result of ion recombination within the chambers air cavity. Recombination can occur due to [26]:

- Ion diffusion against the direction of the electric field.
- ”Initial” recombination between oppositely charged particles formed by the same charged particle or photon interaction.
- ”General” recombination between oppositely charged particles generated from different parent interactions.

Of the different types of recombination, general recombination is dependent on the dose rate being measured. To reduce recombination effects the applied voltage across the chamber can be increased provided that the voltage is still sufficiently low that charge multiplication does not occur. To account for the ion recombination effect and the resulting dose rate dependence an ion recombination correction has to be
evaluated for each beam being measured [16, 17, 26]. By measuring the chamber response using two different applied voltages an ion recombination correction, $P_{\text{ion}}$, can be approximated to within 0.2 % for a continuous non-pulsed beam as [16]:

$$P_{\text{ion}}(V_H) = \frac{1 - \left(\frac{V_H}{V_L}\right)^2}{\frac{M_H}{M_{\text{raw}}}} - \left(\frac{V_H}{V_L}\right)^2$$

(2.10)

Where, $V_H = 2V_L$, and denotes the applied chamber voltage.

In the case of measurements where the field size is small relative to the collecting volume of the chamber, a volume averaging correction is required, $k_{\text{vol}}$ [16]. Additionally, the validity of the remaining correction factors must be verified. The basis of kV dosimetry with ion chambers is $N_k$, measured by a primary standards lab in a beam of matching quality to the beam being measured. Equation 2.9, once all influence quantities are included, becomes:

$$D_{w,2cm} = MN_K P_Q \left[\frac{\rho_{\text{water}}}{\rho_{\text{air}}}\right] P_{\text{ion}} P_{\text{pol}} k_{\text{env}} k_{\text{vol}}$$

(2.11)

The air-kerma rate of a beam of quality $Q$ is commonly determined by a standards lab, such as the National Research Council Canada. A free-air chamber, FAC, is a metrology standard used to determine the air-kerma rate of a beam with the lowest possible uncertainty using ionometric methods. A schematic of a FAC is shown in figure 2.3. The operating principle of a FAC requires that the x-ray beam does not interact with the chamber walls. The chamber is large enough, that if an interaction occurs in the plane of the aperture any secondary electrons produced do not have sufficient energy to reach the collecting volume, shaded in figure and defined by the aperture. This means that the secondary electrons that do reach the collecting volume must be produced in the air volume enclosed by the chamber, $0.25 \, m^3$ for the NRC.
Figure 2.3: A free air chamber schematic. The beam is incident from the left and is defined by the aperture, the collecting volume is shaded. The dimensions of the FAC are chosen such that the beam does not interact with the chamber walls. Charge collected is representative of all the charge released by the beam in the collecting volume, under charged particle equilibrium conditions, allowing the air-kerma rate to be determined.

standard for energies below 300 kVp [30].

To determine the air-kerma in the shaded volume the electrons set in motion outside it, but deposit some of their energy within the volume must be considered. It can be shown, if one neglects the attenuation of the x-ray beam, that for every one of these electrons originating outside the volume, there is an identical electron originating inside the collecting volume that escapes before depositing all of its energy [25]. One can therefore say that the collecting volume is under charged particle equilibrium. Once the attenuation of the photon beam is taken into account, the charge collected by the free air-chamber can be related to the air-kerma in the collecting volume [30].

To reduce the influence of both ion recombination and the polarity effect, FACs are designed to produce a uniform electric field throughout the collecting volume while being operated at a sufficiently high voltage [30]. The air-kerma for a beam can then
be determined from the charge collected as:

\[
K_{air} = \frac{Q_{air}}{\rho_{air} \cdot V} \cdot \frac{W}{e} \cdot \frac{1}{1 - g} \cdot K_{att,sc} \cdot P_{pol} \cdot P_{ion}
\]  \hspace{1cm} (2.12)

Where, \( g \) denotes the radiative yield the fraction of secondary electron kinetic energy lost to radiative (photon producing) processes, \( K_{att,sc} \) a scatter and attenuation correction, and \( \frac{W}{e} \) the mean energy required to form an ion pair in dry air. The large size of FACs and the substantial efforts required to develop a reproducible measurement setup mean they are not often found outside of a standards lab. However, by determining the air-kerma with a low standard uncertainty, on the order of 0.25 %, they are typically used to calibrate the much more practical thimble ion chambers. From equation 2.12 the \( N_K \) factor can be readily derived from the fully corrected ion chamber reading in the same beam being measured as the FAC as:

\[
N_K = \frac{K_{air,FAC}}{M_{chamber}}
\]  \hspace{1cm} (2.13)

Ion chambers used to perform absorbed dose measurements in medium energy x-rays following the TG-61 protocol, equation 2.9, with an \( N_K \) determined by an accredited standards lab for the beam quality of interest provide absorbed dose to water measurements with an uncertainty on the order of 3.6 % [17]. This uncertainty assumes:

- The beam quality of the beam being measured matches the calibration beam, in both kVp and HVL, used to derive \( N_K \).
- The measurement is performed at the reference depth of 2 cm in a water phantom.
- The beam is sufficiently large and uniform over the chambers collecting volume.
The main contributors to the overall uncertainty are the spectrum averaged mass energy absorption coefficient and the difference in the beam quality between the calibration and the beam being measured. Both these uncertainty contributions are a result of the beam quality specifiers used not fully characterizing the energy spectrum of the beam being measured. Despite this, the protocol provides sufficient accuracy, < 5%, to determine the absorbed dose for radiation therapy while maintaining a relatively straightforward measurement procedure.

### 2.2.2 Chemical Dosimeters

Chemical dosimeters relate the amount of a chemical species produced as a result of a chemical reaction to absorbed dose. Radiochromic film and Alanine are two common chemical dosimeters. Radiochromic film is composed of an emulsion containing a radiosensitive monomer incorporated in a gelatin matrix [31, 32]. Radiation induced polymerization of diacetylene molecules form polydiacetylene dye polymers that change the optical absorption properties of the film [31, 32]. By measuring the intensity of light transmitted through an irradiated film a measure of the dose can be obtained.

The quantity of interest in film dosimetry is the optical density, \( \log_{10}(\text{transmission}^{-1}) \), the quantity is typically measured using a tabletop scanner, providing adequate sensitivity in the visible light range, 400-700 nm [32].

Figure 2.4 shows a calibration curve used to convert the change in optical density to absorbed dose. The optical density has a non-linear relationship to the absorbed dose. The non-linearity of the film is accounted for by using a fourth degree polynomial fit of a calibration curve as shown in figure 2.4, to derive the dose as a function of optical density. Additionally, variation between film batches means that a calibration curve has to be determined for each batch of film used. Once irradiated the film
**Figure 2.4:** A typical calibration film measurement in an MV beam produced by a linac, each film was exposed to a predetermined dose traceable to the MV beams calibration. An MV beam produces photons in the MeV range. The different color lines indicate fourth degree polynomial fits to the data, to be used to equate the film response to absorbed dose in different beams. The colors denote the three different scanner color channels.

should be allowed to develop for 48 hours at room temperature, due to the observed growth in the optical density signal post-irradiation due to continuing polymerization [32]. There is no observed correction for environmental conditions provided that both irradiation and readout of measurement/calibration films occurs at room temperature [32]. Film manufactures typically recommend measurement be limited to a dose range on the order of 0.01 - 20 Gy to maintain sensitivity of film response [33]. Several investigations have also shown that film is dose rate independent, for dose rates up to
3 kGy/s [34–38].

A major obstacle in the use of film in the kV x-ray range as an absolute dosimeter is the intrinsic energy dependence and absorbed dose energy dependence. Film manufacturers selectively dope the film’s active layer to achieve energy independence over a wide energy range, a few MeV to 40 keV [32]. Despite these efforts the absorbed dose energy dependence of film has been found to result in a 0.7-5 % effect between 11.5 and 140 keV [39, 40]. Quantifying the absorbed dose energy dependence is also problematic as the sensitivity to the photon energy spectrum leads to inconsistent results with conventional beam quality specifiers [39], changes in absorbed dose energy dependence between film batches have also been observed [40].

Few rigorous metrological radiochromic film studies currently exist in the literature. Hammer et al attempted to measure the intrinsic energy dependence of film for kV beams and estimated a 3-7 % effect between 11.5 and 140 keV [39]. The polymerization reaction only requires energy on the order of several eVs to occur, as a result the large intrinsic energy dependence in the keV range is surprising. Hammer et al attributed this to the spatial distribution of the radiosensitive monomer throughout the gel [39]. The distribution of secondary electron tracks in the gel will be a function of the beam quality, and different distributions will have different likelihoods of interacting with the radiosensitive monomer due to their spatial distribution [39]. Both the absorbed dose and intrinsic energy dependence can be overcome if the calibration curve is generated for the beam being measured, or a beam with an identical energy spectrum. This requires knowledge of the beam’s dose rate which limits the usefulness of film as an absolute dosimeter.

Radiochromic film however, excels in producing high resolution two dimensional dose distributions, with measurements being successfully demonstrated at the microm-
eter scale [41]. In contrast to other chemical dosimeters, film is relatively easy to handle and store. Film can also be readily cut to size depending on the application, and has seen wide use in clinics to measure relative dose distributions [42–44].

Alanine dosimeters are made up of the crystalline amino acid alanine and are typically produced in pellet form, figure 2.5. When irradiated an alanine sample produces free radicals, molecules with free unpaired electrons. An electron paramagnetic resonance, EPR, spectrometer is then used to measure the free radical concentration [45]. An EPR spectrometer uses a magnetic field to split the degeneracy of $e^-$ spin states, microwave energy is then applied to the dosimeter at a fixed frequency. A peak in the absorption of microwave energy is a function of the magnetic field strength $B_0$ and the microwave frequency $v$, satisfying the resonance condition; $v = 2.8026 \cdot 10^{10} B_0 \text{ Hz/T}$ [46–48].

By varying the magnetic field strength a derivative of the absorption spectrum can be obtained and the peak to peak height figure 2.5, $M_{Al}$, is used as a measure of

![Figure 2.5: Left: An Alanine pellet with a diameter of 4.8 mm and a height of 3.0 mm. Right: An EPR spectrum for a cobalt-60 irradiated alanine pellet with the peak to peak height shown.](image)
the free radical concentration. The dose to the alanine can be derived as:

\[ D_{Al} = \frac{M_{Al}}{m_{Al}G_{Al}k_{EPR}} \]  

(2.14)

Where, \( m_{Al} \) is the mass of the alanine sample and \( k_{EPR} \) is a proportionality constant relating the EPR signal to the radical concentration. \( G_{Al} \) denotes the radiation chemical yield of free radicals, the number of free radicals produced per unit energy deposited in the sample. The EPR signal varies unpredictably immediately following irradiation and most measurement protocols require waiting for at least 48 hours for the signal to stabilize [48]. However, once the signal has stabilized and if the pellet is stored under controlled environmental conditions, the signal is reproducible at the \(< 1\%\) level after a year of storage [49]. Similar to radiochromic film, a major obstacle to the use of alanine in the kV range is the accurate determination of the absorbed dose energy and intrinsic energy dependence since \( G_{Al} \) is not known.

The absorbed dose energy dependence can be determined using radiation transport simulations but it ultimately depends on knowledge of the chemical composition of the alanine pellet and of the incident energy spectrum. An absorbed dose energy dependence on the order of 25 \% is observed for photons with an effective energy of 50 keV relative to cobalt-60 [50–53]. The radiation chemical yield in equation 2.14 quantifies the intrinsic energy dependence of the dosimeter. Zeng and McCaffrey estimated the radiation chemical yield was on the order of 5 \% lower for a 150 kVp beam relative to cobalt-60 [53]. Like film, the spatial distribution of secondary electrons in the alanine pellet impacts the number of measurable free radicals formed, consequently an under response of the alanine in kV x-rays relative to cobalt-60 is observed [51–53].

A major advantage of alanine is the dosimeter’s linear dose response over a wide
energy range, up to 5 kGy [54], and dose rate independence, up to $3 \cdot 10^{10}$ Gy/s [55]. The number of free radicals produced is temperature dependent and consequently the alanine signal must be corrected for differences between irradiation and room temperature, a correction of 0.2 % per degree difference [56]. The humidity level affects alanine in two ways; storage at low humidity conditions reduces signal fading, and differences between storage and readout humidity effect the measured EPR signal [57].

The dose rate independence and proven operation at high doses make alanine ideal for industrial applications [58, 59], their ease of transport and energy independence in the MV energy range also makes them ideal reference dosimeters for clinical applications [45, 60]. However, each alanine batch must be calibrated using a radiation source of known dose rate, limiting its use as an absolute dosimeter, particularly in the kV range due to changes in the intrinsic and absorbed dose energy dependence as a function of beam quality.

2.2.3 Solid State Dosimeters

Solid state dosimeters typically relate the excitation of electrons in a semi-conductor, in a region depleted of charge carriers, to the absorbed dose. Solid state dosimeters typically offer high spatial resolution, instant readout and high sensitivity per unit active volume relative to ion chambers due to their higher density [61]. Solid state detectors tend to be made of silicon which has a larger number of electrons per atom relative to water, this results in a large absorbed dose energy dependence in the kV range particularly at the lowest energies, where the photoelectric effect dominates radiation interactions [61, 62]. Diamond detectors are a class of solid state detector whose sensitive volume is composed primarily of carbon atoms, which have a reduced
energy dependence relative to silicon based solid state detectors.

Figure 2.6 shows a microDiamond (PTW 60019, Freiburg, Germany) detector, the inset image shows a planar x-ray image of the detector with the active volume labeled. The superior spatial resolution of the detector is the result of the small sensitive volume of the diamond, a 3 mm diameter by 1 µm thick disc [63], the resolution can be further improved by operating the diamond in an edge on orientation as shown in figure 2.6 [64].

A contact is formed between a metal electrode and the diamond, forming a Schottky diode and resulting in an electric field within the diamond [65]. Modern diamond detectors such as the microDiamond, do not require an external voltage to maintain the electric field formed. When radiation deposits energy within the diamond, the electric field separates the resulting oppositely charged charge carriers, that are liberated within the semiconductor [66, 67]. Somewhat similarly to the operation of an ion chamber the charge is collected at the metal/diamond contacts and can be measured using an electrometer. Diamond detectors exhibit a high sensitivity to incident radiation relative to ion chambers, this can be attributed to both their higher
mass density and the lower amount of energy required to raise an electron to the conduction band $\sim 13$ eV relative to $33.97$ eV required to ionize air [67].

The charge collected by the diamond is weakly dependent on the ambient temperature, a change in response of $< 0.1\%$ per degree change in temperature below $50 ^\circ C$ being measured [68]. Relative to other semiconductor detectors, diamond has proven to be resistant to radiation damage, with operation demonstrated at dose rates on the order of several $kGy/s$ in proton beams [69]. Unfortunately, the charge collected is a function of dose rate and is typically accounted for by fitting the charge collected (as a function of dose rate) to a power-law function of the form:

$$M(\dot{D}) = k\dot{D}^{\Delta}$$  \hspace{1cm} (2.15)

Where, $\Delta$ denotes a fitting parameter that is on the order of 0.98 and $k$ a proportionality constant [70, 71]. This of course requires knowledge of the dose rate of the beam being measured and is a major obstacle to the use of diamond detectors as an absolute dosimeter.

Investigations into the intrinsic energy dependence of diamond for beams with an effective photon energy of between 20 and 130 keV, showed an over-response of the diamond of between 1.1 and 2.5 relative to cobalt-60, when accounting for differences in absorbed dose energy dependence [72]. The absorbed dose energy dependence has also been calculated to be between 0.79 and 1.57 for beams between 250 kVp and 40 kVp relative to cobalt-60 [70]. In addition variations in absorbed dose energy dependence have been reported between identical detectors, indicating a lack of reproducibility of their manufacturing process [73].

The challenges described make diamond inappropriate as an absolute dosimeter. However, diamond detector’s high spatial resolution, instant readout and dose sensitiv-
ity make them an ideal relative dosimeter. The use of diamond detectors to measure depth-dose and beam profiles for kV beams has been successfully demonstrated in the literature [61, 70, 73, 74].

2.2.4 Calorimetry

Calorimeters measure the radiation induced temperature rise in a detector medium, often called the core, and are the most widely used absorbed dose primary standard. Relating the radiation induced temperature rise to the absorbed dose to the core, is conceptually simple:

\[ D_{\text{core}} = \frac{E_{\text{dep}}}{m_{\text{core}}} = c_{\text{core}} \Delta T \]  

(2.16)

The radiation induced temperature rise \(\Delta T\) in the core is directly proportional to the dose, with the proportionality constant being the specific heat capacity, \(c_{\text{core}}\), of the core material. \(c_{\text{core}}\), is the property that ultimately determines the sensitivity of the calorimeter, lower values of \(c_{\text{core}}\) result in larger radiation induced temperature rises per unit dose. A major assumption in equation 2.16 is that all the energy deposited in the detector appears as a temperature rise. In the case of water calorimeters this assumption is no longer valid, radiation induced chemical reactions occur and consume or release energy, changing the measured temperature rise [75, 76]. This heat defect is a function of the concentration of trace impurities in the water, and requires additional considerations to be adequately reduced [75, 76]. A heat deficit correction, \(k_{hd}\) must then be applied to the measured temperature rise to take this into account. In addition, it is not possible to fully thermally isolate a calorimeter as well, and consequently heat losses will occur. Heat losses occur due to temperature gradients within the calorimeter, and can result from [77]:

25
• The presence of non-core material with significantly different heat capacity.

• An inhomogeneous temperature distribution prior to irradiation.

• Energy deposition from the temperature sensors.

Typically water calorimeters are operated at 4 °C, the temperature at which water density is a maximum, to reduce heat losses due to convection, as a result conduction is the main heat-loss pathway of concern for absorbed dose calorimetry. Numerical simulations are used to model the heat transfer away from the core during and after irradiation, by solving the heat transport equation [27, 77–79]. A correction factor for conductive heat losses can then be derived, $k_{ht}$. The magnitude of $k_{ht}$ is a function of irradiation time for any given calorimeter design and potentially beam quality, as different beams would result in different dose gradients within the core itself.

The absorbed dose energy dependence of the calorimeter is accounted for using a Monte Carlo calculated perturbation correction, to correct for the presence of non-core material in the beam path [77]. The ultimate goal is the realization of absorbed dose to water, and consequently an additional Monte Carlo calculated material conversion correction is necessary for non-water calorimeters. A combined Monte Carlo calculated material and perturbation correction, $k_p(Q)$, is used in equation 2.17, with Q denoting the beam quality dependence of the correction. The fully corrected calorimeter dose equation then becomes:

$$D_{water} = c_{core} \Delta T k_p(Q) k_{ht} k_{hd}$$  \hspace{1cm} (2.17)

To successfully perform a calorimetry measurement, the radiation induced temperature rise must be accurately measured. A temperature rise of 0.25 mK/Gy is
expected in water, requiring temperature measurement at the $\mu K$ level to achieve an acceptable measurement uncertainty [80]. All calorimeter based absorbed dose standards use negative thermal coefficient, NTC, thermistors, to measure temperature rise [80]. NTC thermistors are passive components whose resistance decreases as a function of temperature. Although this decrease is non-linear, it is well characterized in the temperature range of interest for absorbed dose calorimeters [80, 81]. The small temperature changes being measured mean that the power dissipation in the thermistors could potentially impact the temperature measurement, and must be investigated [80, 82].

Thermistors can be operated in DC, and the resistance measured directly using a high stability digital multimeter. However, the signal to noise ratio of the measured change in resistance can be improved using a DC Wheatstone bridge or one of several designs of AC bridges [83].

Water calorimeters have been successfully used to determine the absorbed dose to water for 80 kVp to 300 kVp x-rays [84–86]. Most water calorimeters for kV X-rays are similar to those designed to measure clinical energy photons (1.25 MeV - $\gg$10 MeV), but with smaller dimensions to facilitate measurements at shallower depths in phantom. Water calorimeters do not require a material conversion, and water’s low thermal conductivity allows the absorbed dose to be determined at the point of measurement of the temperature probe, in the medium of interest [77]. The Laboratoire National Henri Becquerel, LNHB, medium energy absorbed dose to water calorimeter standard for medium energy x-rays is shown in figure 2.7.

Water calorimeters are made up of a water phantom, and a smaller quartz or glass vessel containing a volume of high purity water. The high purity water is either saturated with an inert gas or hydrogen and pre-irradiated to several hundred grays to
control the number of reactive species produced, resulting in a negligible heat defect $k_{hd} = 1.0$ [75, 84–86]. Quartz or glass vessels are used to avoid contaminating the high purity water, and are kept at a temperature of 4 °C to eliminate convection based heat losses. Before irradiating the water, within the inner vessel, the beam has to travel through; the thermal insulation, PMMA wall of the phantom and the glass/quartz vessel wall. This can result in a significant perturbation correction, $k_p$. Monte Carlo calculated $k_p$ values are strongly dependent on knowledge of the incident beam energy spectrum and can be on the order of 8 % for the lowest energy beams [85, 86]. Despite the size of this correction it is well characterized, provided that the incident beam energy spectrum is accurately modeled, with typical standard uncertainties on

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**Figure 2.7:** Left: The LNHB medium energy x-ray absorbed dose standard, with thermal insulation removed from the front face and top of the PMMA water phantom. Right: A close up view of the quartz vessel containing high purity water, saturated with $N_2$ gas, the two temperature probes are visible protruding into the vessel. Image reproduced from B. Rapp et al. “The LNE-LNHB water calorimeter for primary measurement of absorbed dose at low depth in water: application to medium-energy x-rays”. In: Physics in Medicine & Biology 58.9 (Apr. 2013), p. 2769. [86] with permission of IOP Publishing, Ltd.
the order of 0.5% being reported [77].

In traversing the inner vessel wall, the beam deposits a significant amount of energy, resulting in an increase in temperature of the inner vessel. Since the specific heat of quartz is significantly lower than water, a temperature gradient will exist between them. The temperature gradient can result in excess heat being transferred, from the vessel wall to the water. This can be modeled using the same numerical simulations used to derive the heat conduction correction and a combined correction for conductive heat losses and excess heat ranging between 0.964 and 1.061 is reported [84–86]. Combined relative standard uncertainties on the absorbed dose to water, using water calorimeters, below 1.5% in kV beams has been successfully demonstrated [84–86].

Graphite calorimeters have also been used to measure the absorbed dose to water in kV beams. Graphite is a solid, minimizing the need for non-core material in the beam path, in addition to having a specific heat 1/6 that of water, providing six times the signal to noise ratio. The use of a graphite absorber requires a material conversion, to determine the dose to water, which introduces an additional energy dependence. Crucially, however, graphite has a thermal conductivity on the order of 600 times that of water meaning that the dose derived is averaged over the entire absorber volume, and is no longer the dose at the point of the temperature measurement. Higher thermal conductivity also allows graphite calorimeters to be operated in one of three modes [77]:

- Quasi-adiabatic radiation mode: The core temperature is measured over time in the absence of external energy sources, once the core temperature is stable it is irradiated.
• Quasi-adiabatic electrical mode: The core temperature response to a given amount of electrical heating is measured in the absence of radiation and used to establish an effective “heat-capacity” for the core, to serve as a calibration factor when the core is irradiated.

• Isothermal mode: When the calorimeter is irradiated, the amount of electrical energy required to keep the calorimeter temperature constant is measured, which can then be used to determine the energy imparted by the radiation.

Pinto et al. developed a graphite in water calorimeter, figure 2.8, with a disc shaped core encased in PMMA to facilitate measurements in a water phantom [87]. Figure 2.8 shows a cross-section of the calorimeter, the nested design reduces heat transfer away from the core, since the different graphite layers will be at the same temperature during irradiation. In addition, vacuum gaps are used to further reduce heat transfer between the different layers. Several heating thermistors in the graphite layers surrounding the core allow the calorimeter to be operated in quasi-adiabatic electrical mode.

Numerical simulations provided estimates of the conductivity correction that were less than 0.5 %, indicating adequate isolation of the core [87]. The presence of non-graphite materials in the core such as the thermistors and adhesives used resulted in a large Monte Carlo based correction to determine the energy deposited, an 11 % correction for an effective photon energy of 87 keV [87]. The graphite calorimeter design was able to realize the absorbed dose to water with a relative standard uncertainty of less than 2 % [87]. The two largest contributions to the uncertainty being the Monte Carlo based corrections for converting from graphite to water, and the determination of the energy deposited in the core, in the presence of
Figure 2.8: A schematic of a graphite calorimeter designed for medium energy x-rays. (1)Core (2)Jacket (3)Shield (4)Vacuum gaps (5)PMMA envelope. Image reproduced from M. Pinto et al. “A graphite calorimeter for absolute measurements of absorbed dose to water: application in medium-energy x-ray filtered beams”. In: Physics in Medicine & Biology 61.4 (Feb. 2016), p. 1738. [87] with permission of IOP Publishing, Ltd.

non-core material.

Both water and graphite calorimeters provide a measurement of the absorbed dose that is entirely independent of measurements made using radiation sources other than the source being measured. Water calorimeters are also the only detector to provide a direct measurement of the quantity of interest, absorbed dose to water. As a result calorimeters are the most common type of absorbed dose standard, particularly for MV photon beams [80]. Of the detectors discussed in this section only the free-air chamber can claim to be a similarly independent measurement, and provides air-kerma standards in kV beams in many standards labs [80].

Not unlike free-air chambers, calorimeters are typically large, when the insulation and phantom is considered. Calorimeters tend to also be fragile and often require specialized readout equipment / circuitry, with probe type graphite calorimeters and
compact graphite calorimeters designed for clinical beams being notable exceptions [87–89]. The reproducibility of the calorimeter measured temperature rise is expected to improve at higher dose-rates, allowing for greater temperature rises to be measured while decreasing the irradiation time, limiting the influence of conductive heat-losses during irradiation. Although the ability to measure dose at a point for water calorimeters and the ability to modify the core shape to minimize volume averaging affects in graphite calorimeters is advantageous for small fields, the need for a relatively large thermal mass of uniform temperature to minimize heat-losses is a major obstacle to their use.

### 2.3 Synchrotron Radiation

#### 2.3.1 Introduction

The properties that make synchrotron photons a desirable research tool, their high dose rate, collimation and energy are a direct result of the underlying physics of synchrotron radiation production. This section aims to describe how synchrotron radiation is produced. An understanding of the mechanisms behind how synchrotron radiation properties arise and how they can be altered is an important step in understanding the design requirements for a purpose built dosimeter.

When a relativistic charged particle is deflected by a magnetic field electromagnetic radiation is released. This phenomenon can be exploited in circular particle accelerators to produce intense sources of electromagnetic radiation. The radius of a charged particle’s orbit, under the influence of a constant magnetic field, is proportional to its energy [90]. To keep a charged particle of increasing energy, in a circular path of fixed radius, the magnetic field must be increased. By synchronously changing the magnetic
field, as the electron energy is increased in a circular electron accelerator, electrons can be accelerated to energies on the order of several GeVs. The yield and energy of electromagnetic radiation can then be increased, when the high energy electrons are deflected by a magnetic field, this is the operating principle behind a synchrotron light source [90]. The main components of a light source are shown in figure 2.9.

The injector is responsible for the production of electrons and accelerating them to their target energy, on the order of several 100 MeVs. A linear accelerator is used as the injector. By heating a cathode electrons are released through thermionic emission.

**Figure 2.9:** A functional diagram of the main components of a synchrotron light source. The electrons, shown in yellow, are generated and accelerated to an energy on the order of several hundred MeV using a linear accelerator, linac. The booster ring further increases the electron energy to their maximum energy, typically on the order of several GeV for most modern light sources. The storage ring maintains the electron energy and compensates for losses incurred as the electrons orbit the ring and release synchrotron radiation, shown in white. Different beamlines are present along the storage ring, with specialized insertion devices to modify the properties of synchrotron radiation for use.
Powerful radio-frequency, RF, fields are generated using a klystron, and are used to increase the energy of the electrons to the target energy [91]. The next stage of the injector system involves the use of a circular accelerator, called the booster ring. Dipole magnets are used to maintain the electrons in a constant circular orbit, as RF fields are continuously applied to increase their energy. To achieve this both the dipole magnets and RF fields must increase synchronously [91]. Once the desired energy is achieved, often on the order of several GeVs, the magnetic fields are adjusted to transfer the electrons to the next stage, the storage ring.

The storage ring is comprised of a series of straight sections constituting different beamlines. To maintain the electron orbit, a series of bending magnets are located throughout the ring. In addition, RF cavities compensate for electron energy losses due to interactions within the storage ring and the release of synchrotron radiation, SR [91]. An ultra-high vacuum, $< 1 \cdot 10^{-13} \text{mbar}$, is essential to reduce energy losses and to maintain the current in the storage ring. Despite this, if new electrons are not added by the injector, the beam current falls exponentially [92]. Synchrotrons can be operated in top-up mode where the injector continuously adds electrons into the storage ring maintaining a near constant beam current, at the 0.1 % level [93].

SR is produced when electrons pass through the bending magnets and through different magnetic arrays at the different beamlines, called insertion devices. Insertion devices affect the energy, polarization and size of the beam depending on the beamline’s intended use.

Several unique properties of SR make them valuable research tools. The number of photons produced is several orders of magnitude higher than conventional kV x-ray tubes. These photons are concentrated in a narrow cone, resulting in smaller field sizes but an extremely bright light source and consequently a high dose rate beam.
Synchrotron sources are often, $10^7$ times brighter than conventional x-ray tubes, when produced with specialized insertion devices. The larger photon flux allows the selection of single energies, using specialized monochromators, while maintaining a sufficient number of photons, which would be impractical for a kV x-ray tube.

The electron energy in the storage ring and magnetic arrays determine the photon energy spectrum produced. A broad energy spectrum, figure 2.10, is produced between 1 meV to 100s of keV allowing a wide array of experiments, at different beamlines, supplied by the same storage ring. The critical energy, $E_c$, is defined such that the total integrated power below and above that energy is equal [91], and used to describe the energy spectrum of a synchrotron source.

Figure 2.11 shows the dipole angular distribution for a non-relativistic charged particle. For an ultra relativistic charged particle, relative to an observer in the lab frame, the angular distribution collapses into a cone whose opening angle is inversely proportional to the electrons energy. If a single electron was orbiting the storage ring, the radiation emitted would appear similar to a sweeping search light in the lab frame. For a single electron the divergence of SR produced would be less than a milli-radian [90, 91]. Since the electron beam is made up of many electrons spatially distributed within bunches orbiting the storage ring, the divergence is somewhat greater. The sweeping search-light analogy can also be used to explain the greater horizontal extent of the field size produced. Since the electrons emit SR at a tangent relative to the horizontal circular orbit, the horizontal collimation is lost [91].

The SR beam will be polarized, the direction of which will depend on the type of insertion device used. The polarization, and the ability to modify it, facilitates imaging studies of some materials [95]. The angular dependence, of energy-transferring radiation interactions with matter will also be modified, which can impact dosimetry
The coherence of some SR photons allows the use of phase-based x-ray imaging, in addition to interference studies. SR is produced in pulses, as different electron bunches reach the beamline. The pulse repetition time depends on the frequency of the storage ring RF cavities, and is on the order of nano-seconds with pulse widths on the order of pico-seconds. The coherence of SR photons, particularly when a monochromator is used to select a single energy, allows their use in phase-based imaging studies [97].
2.3.2 Synchrotron Radiation Production Physics

To understand the physical mechanism behind synchrotron production, it is best to consider the motion of an electron in a uniform magnetic field. If the electron is non-relativistic, $\beta = \frac{v}{c} \ll 1$, the magnetic field will exert a Lorentz force, perpendicular to the electron's velocity, $v$, and the direction of the magnetic field $B$. If both the velocity and direction of the magnetic field are perpendicular to each other then the electron will undergo circular motion. By equating the Lorentz force to the inertial force acting on the rotating electron the following expression can be derived [96, 98]:

$$m_e\omega^2 r = e(\vec{B} \times \vec{v}) = Bev$$ (2.18)
\[ \omega = \frac{v}{r} \]  
\[ \omega = \frac{eB}{m_e} \]  

(2.19)  
(2.20)

where, \( r \) denotes the radius of the circular path, \( m_e \) the electron mass and \( e \) the electron charge. The electromagnetic radiation produced would then have a single frequency given by \( \omega \) in equation 2.20, a function of the magnetic field strength. An expression for the total power is given by the Larmor formula [98]:

\[ P = \frac{e^2a^2}{6\pi\varepsilon_0c^3} \]  

(2.21)

where, \( a \) denotes the electron’s linear acceleration and \( \varepsilon_0 \) the permittivity of free space.

The distribution of electromagnetic radiation, relative to the emitting electron is shown in figure 2.11. When relativistic effects are taken into consideration, as the electrons velocity increases, both the power and angular distribution of the electromagnetic radiation changes. Liénard’s generalization of the Larmor formulae, in equation 2.21, predicts the total power, by multiplying by the Lorentz factor, \( \gamma = \frac{E}{m_ec^2} \), to the fourth power, as [98]:

\[ P = \frac{e^2a^2}{6\pi\varepsilon_0c^3} \gamma^4 \]  

(2.22)

For a 2 GeV synchrotron produced electron, \( \gamma \) is on the order of \( 4 \cdot 10^3 \), this implies an increase in power relative to a non-relativistic electron of \( 2 \cdot 10^{14} \). This is the main reason behind the intensity of synchrotron light sources, as a result the power is strongly dependent on the electron energy. To qualitatively understand the change in the electromagnetic spectrum, from the monoenergetic one predicted by equation 2.20, for a classical electron, to the spectrum shown in figure 2.10 we will
consider a geometric argument.

If a detector is placed tangential to a point on the electron’s circular path, it will measure a pulse of radiation at a rate equal to the electron’s angular frequency. In the frequency domain the spectra shown in figure 2.10 will be composed of harmonics of this fundamental frequency [91]. The cut-off at high frequency can be explained, since the detector receives radiation along the arc shown in figure 2.12. A photon released at the end of the arc will reach the detector at some time \( \Delta t \) after the photon released at the beginning of the arc, resulting in a pulse width \( \Delta t \). The finite pulse duration will then have frequency components up to a cut-off frequency, consistent with the SR spectrum in figure 2.10 [91]. The SR spectrum and power is then a function of the magnetic field strength. Both the statistical oscillations of the electrons and the statistical nature of the emission of SR lead to a broadening of the individual harmonics making up the energy spectrum, leading to a continuous distribution below the cut-off frequency [91].

There is an energy distribution within the cone of emitted SR as well. This can be attributed to the relativistic Doppler effect [99]. The frequency of emitted SR in the lab frame as a function of the emission angle, \( \psi \) in figure 2.11 can be described as:

\[
f = f_0 \gamma (1 + \beta \cos \psi)
\]  

(2.23)

The highest frequency measured in the lab frame would occur at \( \psi = 0 \), implying that the distribution of energies within the SR emission cone increases towards the center.

The preceding discussion is meant to give a brief overview of the physical processes behind many of the unique properties of synchrotron produced photons. In summary the energy, power and degree of collimation are a function of electron energy. Both
the energy spectrum and power additionally depend on the strength of the magnetic field used.

### 2.3.3 The Canadian Light Source

The Canadian Light Source, CLS, a 2.9 GeV light source located in Saskatoon, Canada, is the main focus of this work. More specifically, we will be using the Biomedical Imaging and Therapy, BMIT-ID, beamline there (figure 2.13). To achieve the high energies and photon flux densities at this beamline a wiggler insertion device is used. A wiggler consists of a series of alternating magnetic poles. As the electrons traverse the wiggler they follow a sinusoidal path, essentially being deflected at each pole, figure 2.14 [99]. The SR produced is equivalent to adding the emissions of a number of

![Figure 2.12: The light pulse duration emitted by an electron traveling through a bending magnet. The detector is meant to record SR emission along the arc A to A’. The graph is meant to illustrate the detector measurement of SR intensity with respect to time. Image reproduced from Antonella Balerna and Settimio Mobilio. “Introduction to synchrotron radiation”. In: Synchrotron Radiation: Basics, Methods and Applications. Springer, 2014, pp. 3–28. [91] with permission of Springer Nature publishing.](image-url)
bending magnets, equal to the number of poles of the wiggler [91, 99]. The wiggler is fabricated such that the electron beam emerges with no change in its circular trajectory in the storage ring, allowing the use of larger magnetic field strengths, relative to the bending magnets present in the storage ring [99]. The higher magnetic field strengths further increase the flux and energy of the SR produced, in essence shifting the curve in figure 2.10 upwards (by increasing the fluence of SR) and to the right (by increasing the critical energy) [91, 99]. The magnetic field of the wiggler can also be changed, to modify the energy spectrum produced.

The BMIT-ID line uses a 4.3 T superconducting multi-pole wiggler, (Budker Institute of Nuclear Physics, Novosibirsk, Russia) [96]. The beam produced has a critical energy of 24 keV, 3 times as large as the bending magnet beamline, a parallel beamline at CLS which relies on a single bending magnet. The three fold increase in critical energy is due to the higher magnetic field strength of the wiggler. Relevant parameters for both the beam and wiggler are given in table 2.1 [96]. Various beam
modifiers such as collimators, filters and monochromators are located between the wiggler and the sample position. Monochromators are used to select narrow energy bandwidths, with a resolution on the order of +/- 0.15 keV [100].

The higher photon fluence makes the use of beam monochromators possible. A Laue/bent-Laue double crystal, Si (1,1,1), monochromator is used [96, 100]. The first crystal determines the energy of the transmitted beam, by diffracting the incident poly-energetic beam off its crystalline planes [101]. Diffraction occurs when the wavelength of the incident beam is comparable to the planar spacing of the crystal [102]. The scattered waves will interfere constructively from successive crystal planes if they satisfy the Bragg condition, \( n\lambda = 2dsin\theta \), where \( d \) denotes the crystal plane spacing and \( \theta \) the angle of incidence.

\[ \text{Figure 2.14: The array of magnets result in the electrons following the sinusoidal trajectory shown. The resulting SR produced is equivalent to adding the emissions of several bending magnets equal to the number of magnetic poles, resulting in a greater flux. The higher magnetic field strengths relative to bending magnets increase the critical energy of the SR spectrum produced as well. Image reproduced from Klaus Wille. The physics of particle accelerators: an introduction. Clarendon Press, 2000.[99] licensed under CC BY 3.0.} \]
**Table 2.1: CLS BMIT-ID beamline properties [96, 100, 103, 104].**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Range</td>
<td>20 - 150 + keV</td>
</tr>
<tr>
<td>Critical Energy</td>
<td>24 keV</td>
</tr>
<tr>
<td>Photon Flux</td>
<td>$3.0 \times 10^{12} \text{ph/s/\text{mA/mrad}^2/0.1%BW at 20 keV}$</td>
</tr>
<tr>
<td>Beamline length</td>
<td>55 m</td>
</tr>
<tr>
<td>Horizontal Divergence</td>
<td>4 mrad</td>
</tr>
<tr>
<td>Vertical Divergence</td>
<td>0.2 mrad</td>
</tr>
<tr>
<td>Beam Size (H) x (V)</td>
<td>224 mm x 11 mm</td>
</tr>
<tr>
<td>Wiggler Magnetic Field</td>
<td>4.3 T max</td>
</tr>
</tbody>
</table>

The Bragg condition specifies that in addition to the fundamental wavelength, any multiple $n\lambda$ of the fundamental wavelength will also be reflected. These harmonics will then influence the monochromaticity of the beam produced. This is of particular concern for lower energy monochromatic beams, and requires the use of low pass filtering optical devices to preferentially attenuate the higher order harmonics produced [105].

At higher energies, $4 \cdot E_{\text{critical}}$, the number of photons decreases exponentially (see figure 2.10) and consequently the intensity of higher order harmonics will be further reduced. For the Si (1,1,1) crystal used, the second harmonic is forbidden, and the first higher order harmonic would occur at 3 times the fundamental energy. If one considers the photon flux to be negligible at $10 \cdot E_{\text{critical}}$, then harmonics can be ignored at beam energies above 80 keV. This was confirmed in preliminary work during the commissioning of the beamline [96].
The second crystal is purposefully bent, cylindrically with the bending axis perpendicular to the diffraction plane of both crystals and used to focus the diffracted beam from the first crystal [101]. The Laue/bent-Laue double crystal is also designed to preserve the divergence of the original beam. The incident beam results in a significant temperature rise, the monochromators must be actively cooled to maintain the intensity of the transmitted beam and avoid scattering losses due to thermal effects in the crystal [96].

In summary the BMIT-ID beamline can produce monochromatic x-ray beams in the 80 - 140 keV range, with negligible contributions from higher order harmonics. The natural collimation and brightness of the source result in a small (224 mm x 11 mm), but non-uniform beam size in the vertical direction. The SR produced would result in smaller vertical beam sizes as higher monochromatic beam energies are selected, since the highest frequency SR will be at the center of the narrow radiation cone emitted. This is in stark contrast to a kV x-ray tube that typically produces a flat x-ray field on the order of 10 x 10 cm, but with a brightness several orders of magnitude lower. The difference in brightness translates directly to a difference in dose rate. The stability of the beam output is also dependent on both the storage ring current and the thermal stability of the monochromator.

These unique properties of SR pose a significant challenge to absolute dosimetry, particularly for the detectors discussed in Chapter 2.2, with a complex energy dependence.
2.4 Literature Review

Dosimetry investigations have been attempted using synchrotron beams. A wide variety of those approaches have been presented in the literature, this review will focus on previous approaches which have shown promise towards absolute dosimetry in synchrotron beams.

The protocols for reference dosimetry in kV x-rays such as TG-61 [17] and TRS-398 [15] are designed for use with kV x-ray tubes. The x-rays produced have larger more uniform field sizes and complex spectra (figure 2.1), while potentially having dose rates orders of magnitude lower than a synchrotron beam.

Relative reference dosimetry has been attempted in synchrotron beams using ion chambers, with calibration factors traceable to kV x-ray tube based standards [5, 6]. Prezado et al [5] attempted to apply the TRS-398 [15] procedure to a 80 keV monochromatic synchrotron beam. To overcome the 3 mm vertical beam size they attempted to scan the beam and in effect uniformly irradiate the chamber. Assessment of the different scatter contributions was made using Monte Carlo modeling of the phantom and chamber [5]. A limitation of this method was the air-kerma calibration factor for the chamber, which was converted to the beam of interest by simulating the energy deposited due to the calibration beam, and the monochromatic synchrotron beam. The simulation assumed a large uniform 80 keV beam, and the calculated beam quality conversion factor had an uncertainty on the order of 1 % [5]. An overall uncertainty on the order of 2 % for the absorbed dose to water is claimed, however both the chamber polarity and ion recombination corrections were not independently assessed and the uncertainties attributed to them were based on measurements performed in a different, lower dose rate, beam. An overall uncertainty for all the influence quantities, equation 2.4, contributing to the chamber measurement on the
order of 1% was reported [5].

Fournier et al [6] took a similar approach to determine the impact of ion recombination on chamber measurements due to a wiggler insertion device at the European Synchrotron Radiation Facility, ESRF. An ion recombination correction on the order of $4.0 \pm 0.6\%$ is determined, for a $40\ Gy\ s^{-1}$ dose rate beam. The ion recombination was determined by varying the dose rate of the synchrotron source, as opposed to using equation 2.10. An overall uncertainty of the absorbed dose to water due to the scanned wiggler field, was determined to be 4.4%, with conversion from a kV tube based calibration to the synchrotron beam quality contributing a 3.7% uncertainty. The need to accurately determine influence quantities particularly ion recombination is highlighted by this work, and is a major obstacle to the use of ion chambers in synchrotron beams. An additional source of uncertainty involves the beam quality conversion from a kV tube produced spectrum, to a synchrotron one.

Of the detectors described in Chapter 2.2 only FACs and calorimeters provide a route to determine the absorbed dose to water, due to a monochromatic beam, that is not traceable to a kV x-ray tube. Nariyama et al attempted to use a FAC to measure the photon fluence of the SPring-8 in Japan, an 8 GeV synchrotron light source [106]. The group faced two main challenges: an inability to accurately measure the non-uniform beam area, made a measurement of air-kerma rate unfeasible and the use of a FAC designed for lower energy beams resulted in large corrections [106].

When attempting to perform a measurement with a FAC the number of electrons depositing energy in the electrodes must be minimized, this can be achieved by increasing the electrode separation as the beam energy increases. An increase in plate separation also requires an increase in the applied voltage, (most FACs are operated at voltages on the order of several kVs) to maintain the electric field strength and
minimize ion recombination. Knowledge of the beam area is necessary as it determines the volume of air irradiated by the beam, figure 2.3, and allows the charge collected per unit mass to be determined.

The measurements were performed using monochromatic beams in the 80 - 150 keV range and would require a plate separation of 27 cm, equal to two times the largest secondary electron range. However, the measurements were performed with a FAC with a 12 cm plate separation. By accurately modeling the chamber and considering the impact of polarization on the resulting radiation interactions, the electron loss correction was estimated to be on the order of 2.5 %, at energies between 80 and 100 keV [106]. The polarization of the synchrotron beam was found to result in a decrease on the order of 2 % in the electron loss correction [106]. As a result, the fluence was determined for the monochromatic beams in the 80 - 150 keV range with an uncertainty of 3 % [106]. Based on this work, an accurate determination of the beam area would allow the air-kerma rate to be measured using a FAC, a first step towards determining the absorbed dose rate.

In an attempt to validate a calculated energy spectrum of the Imaging and Medical Beamline (IMBL) at the Australian Synchrotron, Crosbie et al. performed a series of FAC measurements [7]. A wiggler insertion device was used to produce a polychromatic synchrotron beam, and was collimated to produce a 0.5 mm by 0.5 mm beam. Taking advantage of the low divergence of the synchrotron beam, measurements were performed with two FACs simultaneously, by aligning both chambers along the beam central axis such that it can pass unhindered through both apertures consecutively.

To overcome the challenge of accurately determining the beam area, radiochromic film measurements were used as a relative detector. Consequently, the air-kerma rate
could be determined. The FACs had different plate separations, 60 mm and 11 mm, with calculated electron loss corrections of 1.05 and 1.40 respectively [7]. An estimate of the overall uncertainty on the air-kerma rate for the synchrotron beam of 2.9 % was determined [7]. The air-kerma rate uncertainty was dominated by the beam area uncertainty, 2.6 % [7]. Additionally, the FAC with the 60 mm plate separation showed agreement with the theoretically determined air-kerma rate at the 3 % level, while the smaller FAC consistently underestimated the air-kerma rate by up to 10 %, highlighting the challenges of doing accurate absolute measurements without a purpose built detector.

Anderson et al. [96] used a FAC with a variable electrode length to measure the air-kerma rate due to a lower dose rate bending magnet beamline at the CLS. The bending magnet beamline at CLS is different to the wiggler beamline used to produce the monochromatic beams in our investigation. The FAC aperture was used to define the beam area and was measured with an uncertainty of $\pm 5 \mu m$ [96]. An uncertainty on the air-kerma rate between 2.2 - 13.6 % was estimated for a series of filtered polychromatic beams [96]. With the highest uncertainty largely due to the reproducibility of the charge collected for the heavily filtered, lowest dose rate beam [96].

Despite the accurate knowledge of the aperture size, the beam area was the largest contributor to the overall uncertainty for the beams with reproducible charge collection, with a $\pm 5 \mu m$ change in beam area resulting in a 2 % difference in beam size. In addition to the need to accurately determine the beam size, FACs require significant effort to position in the beam due to their size and weight. The time required to set-up and perform measurements can also be problematic in a beamline where access is limited [7, 96]. In theory, with a purpose built FAC and enough time to accurately
characterize all the influence quantities, the uncertainty on the air-kerma rate and consequently the absorbed dose can be significantly reduced to the 1% level.

Calorimeters measure absorbed dose directly and have improved performance at higher dose rates. To date, the work of Harty et al. [8] is the most comprehensive use of a calorimeter to determine the absorbed dose due to a synchrotron. A graphite calorimeter was used to measure beams with an effective energy of 80 and 90 keV with dose rates on the order of 50 and 20 Gy/s respectively [8]. The calorimeter, originally designed for measuring MeV electron beams, is composed of a central graphite disc (40 mm diameter by 2 mm thick) [8]. Thermistors are used to determine the temperature rise of the central graphite disc, figure 2.15. The small non-uniform synchrotron beam size, 120 mm by 40 mm FWHM, means that the core is partially irradiated.

By assuming that the core temperature reaches an equilibrium shortly after

\[ \text{Figure 2.15: Left: A schematic of the graphite calorimeter used at the IMBL to measure absorbed dose in different beamlines. Right: The irradiation set-up used by Harty et al to measure the absorbed dose due to a synchrotron beam using both a FAC and calorimeter simultaneously. Image reproduced from P. D. Harty et al. “Absolute x-ray dosimetry on a synchrotron medical beam line with a graphite calorimeter”. In: Medical physics 41.5 (2014). [8] with permission of John Wiley & Sons publishing.} \]
irradiation the temperature rise can be scaled by the relative areas of the calorimeter core and beam. Similar to FAC measurements, determination of the beam area is a source of uncertainty. The beam area was derived by using gafchromic film as a relative dosimeter [8]. By placing a FAC, between the core and the beam, measurements using both detectors can be done simultaneously.

To convert the radiation induced temperature rise, reproducible at the 0.5 % level, to absorbed dose to water a Monte Carlo based conversion was performed. The conversion relied on the use of a simulated square uniform beam, 4 x 4 mm, using calculated synchrotron spectra [8]. An overall uncertainty on the absorbed dose to water of 2.7 % was reported [8]. The uncertainty on the Monte Carlo conversion, mainly due to the calculated spectra, was estimated to be 2.49 %, and is a significant contributor to the overall uncertainty on the absorbed dose to water [8]. Additionally, an uncertainty of 0.65 % is a result of the uncertainty in the beam area, which determines the region of the core that is irradiated [8]. Validation of the approach was demonstrated by agreement at the 3 % level, well within uncertainties, between the FAC determined absorbed dose rate and the calorimeter determination [8].

The work of Lye et al. [107] used the same calorimeter to measure the absorbed dose due to a higher dose rate beam at a different IMBL beamline, with an effective energy of 80 keV. The higher dose rate beam, 300 Gy/s, had a significantly smaller beam size in the vertical direction (on the order of 2 mm) [107]. To overcome the beam size limitation, the calorimeter was scanned vertically, such that the absorbed dose could be expressed as $D = \frac{\dot{D} h}{v}$ with $h$ and $v$ denoting the beam height and velocity respectively. The need to scan the calorimeter, to produce clinically useful beam sizes 10-20 mm used for beamline user experiments, introduces an additional uncertainty on the determination of the beam area.
An overall uncertainty on the absorbed dose to water of 2.3 % was determined, with a 1.6 % contribution to the overall uncertainty due to the Monte Carlo based conversion [107]. In this setup, the thermistors were irradiated, unlike in the previous work of Harty et al. [8]. The irradiation of the thermistors resulted in a temperature rise, equivalent to 0.2 % of the overall temperature rise measured [107]. Additionally, investigation of the choice of when to start the post-irradiation linear fitting, contributed to an expanded uncertainty on the measured temperature rise of 1.2 % [107].

The accurate characterization of the associated uncertainties meant that the measured absorbed dose to water was in agreement within uncertainties, < 3 %, with thimble chamber measurements performed in the same beam [107]. Several chamber air-kerma calibration coefficients, derived from narrow beam spectrum measurements in kV x-ray tubes were used [107]. The calibration coefficients were weighted such that the weighted sum of the calibration spectra would approximate the synchrotron produced spectrum [107]. This novel approach is likely to have significantly improved the agreement between the chamber and calorimeter measurements, however it is ultimately limited by the calibration spectra available and knowledge of the synchrotron produced spectrum.

More recently, in an attempt to characterize the energy dependence of alanine at lower kV energies, van den Elzen et al [108] used a graphite calorimeter, figure 2.16 to measure the dose rate of a monochromatic synchrotron beam. Monochromatic beams with energies between 8 and 20 keV were measured, with dose rates on the order of 10 Gy/s and field sizes of 6 x 6 mm [108]. Similar to the work of Harty et al [8] the calorimeter core was partially irradiated [108].

An overall uncertainty on the absorbed does to the graphite core of 1.1 % was determined [108]. When attempting to relate the absorbed dose to graphite to the
Figure 2.16: A cross section of the graphite calorimeter used by van den Elzen et al to determine the dose rate of 8 - 20 keV monochromatic x-ray beams. All shown dimensions are in mm. Image reproduced from P. van den Elzen et al. “Alanine response to low energy synchrotron x-ray radiation”. In: Physics in Medicine & Biology 68.6 (Mar. 2023), p. 065011. [108] licensed under CC BY 4.0.

The goal of this work is to measure the absorbed dose to water due to the 80 - 140 keV monochromatic synchrotron beams produced by the BMIT-ID beamline at the CLS. Wiggler sources, like the BMIT-ID beamline, are in high demand due to their higher energy and dose rate. The high demand results in limited beam access and adds an additional constraint to the detector design chosen for this work. The FACs
discussed have the potential to determine the air-kerma rate with an uncertainty on the order of 1%, for a purpose built chamber. A purpose built chamber would have an optimal operating voltage and plate separation for the photon energy of interest. Additionally, a well characterized aperture size would minimize uncertainty due to the field size which affected the FAC measurements described, while measurement in the monochromatic beams of interest for this work would eliminate the need to model the synchrotron energy spectrum. Unfortunately as reported by some of the works cited in this section [7, 96] setup is both difficult and time consuming. While such measurements may be feasible during commissioning, as was the case with Anderson et al [96], limited ongoing access to the wiggler beamline make them impractical.

The graphite calorimeters discussed are promising for use in measuring the beams of interest in this work. Particularly, the scanning approach of Lye et al [107], when one considers that a major contribution to the overall uncertainty was the determination of the synchrotron energy spectrum and the resulting sensitivity of the graphite to water conversion. This would necessarily decrease for use in a monochromatic beam. Additionally, all the calorimeters discussed were originally designed for use in other, larger beams. The smaller field size of the synchrotron beam meant that the calorimeter cores were partially irradiated as the beam was smaller in 2 dimensions. Thermal modeling of the heat flow during irradiation, can reduce the temperature uncertainty measurement as well. Thermal modeling could allow the impact of the time chosen to apply the post-irradiation fit, which resulted in the expanded uncertainty on the temperature rise measurement reported by Lye et al [107], to be quantitatively assessed and corrected for. The beam area is a significant source of uncertainty, a purpose built calorimeter, with a significantly smaller core, could minimize the uncertainty due to the partial irradiation of the core and in doing so limit the sensitivity to the
beam area in one or more dimensions.

Based on the literature a purpose built calorimeter would facilitate measurements in the beams of interest, with a well characterized and lower uncertainty than ion chamber based protocols for kV x-ray tubes. The calorimeter design would have to address the sensitivity to the beam profile/area, and the uncertainty on the dose to water material conversion, while being both portable and easily set-up at the CLS.
Chapter 3

Detector Design

3.1 Beam Characterization

The purpose of this section is to outline the characteristics of the BMIT-ID monochromatic beams that will impact the design of a calorimeter. Based on the literature review the following properties of the beam need to be determined:

- An order of magnitude estimate of the dose rate.
- A high resolution measurement of the beam profile/area.
- The stability of the monochromator output.

Preliminary data provided by the CLS for the beamline was presented in table 2.1. Based on figure 2.10, as the monochromatic beam increases in energy the dose rate should decrease significantly. The lowest dose rate, and therefore highest energy beam, provides a limit for the sensitivity required of the calorimeter design.

To determine an order of magnitude estimate of the beam’s dose rate, air-kerma measurements were performed using an Exradin® A1SL ion chamber (Standard
Figure 3.1: The variation of air-kerma calibration factor, traceable to the NRC’s FAC medium energy x-ray standard, with respect to beam quality for a series of narrow beam spectra closely matching the monochromatic beams measured at the CLS.

Imaging, Middleton, WI). The chamber was calibrated at the NRC using a series of ISO 4037-1 Narrow beams [109], with effective energies ranging from 65 – 166 keV. The air-kerma rate was determined using the NRC free-air chamber air-kerma primary standard. It should be noted that the air-kerma and dose to air can be considered equivalent in this energy range. The calibration uncertainty is conservatively taken to be 0.5 %, while the greatest variation between different beam air-kerma calibration factors was 2.3 %, figure 3.1.

Charge measurements were performed in air, by aligning the center of the chamber’s
Table 3.1: Air-kerma measurements performed using an Exradin® A1SL ion chamber for five monochromatic beams at the BMIT-ID beamline, operated at 2.7 T. Nominal values were provided by CLS and based on measurements performed using a PTW Pinpoint chamber.

<table>
<thead>
<tr>
<th>Energy (keV)</th>
<th>CLS Nominal $K_{air}$ (mGy/s)</th>
<th>Measured $K_{air}$ (mGy/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>65</td>
<td>943</td>
<td>771</td>
</tr>
<tr>
<td>83</td>
<td>452</td>
<td>297</td>
</tr>
<tr>
<td>100</td>
<td>131</td>
<td>100</td>
</tr>
<tr>
<td>115</td>
<td>46</td>
<td>35</td>
</tr>
<tr>
<td>140</td>
<td>6</td>
<td>5</td>
</tr>
</tbody>
</table>

Collecting volume to the center of the beam using a SCMOS, PCO Edge 5.5 (Excelitas Technologies, Kelheim, Germany), based camera with a resolution on the order of 6.5 $\mu$m. The results are summarized in table 3.1. The air-kerma rate was calculated by multiplying the corrected charge reading, calculated using equation 2.4, by the air-kerma calibration coefficient for the beam quality with the corresponding effective energy. The limitations of this approach have been discussed in the literature review, but the use of kV x-ray tube calibrated ion chambers provide a route for an order of magnitude assessment of the beam’s dose rate. All corrections for influence quantities were calculated based on the TG-61 protocol [17], described in section 2.2.1. In addition, table 3.1 shows nominal air-kerma rate values provided by the light source, the nominal values were determined using an ion chamber, PTW Pinpoint (Freiburg, Germany), with a manufacturer provided air-kerma calibration, traceable to a kV x-ray tube.

At the time, the wiggler was operated at 2.7 T, reducing the dose rate relative
to the maximum wiggler field strength of 3.7 T, due to beamline constraints. The beam profile was also unknown, limiting the validity of attempts to correct for volume averaging over the chamber’s sensitive volume. The large disagreement between the NRC measured air-kerma rate and the nominal air-kerma rates provided, are a likely result of volume averaging. The A1SL chamber has a larger collecting volume, 0.053 cm$^3$, and consequently consistently underestimates the dose relative to the Pinpoint chamber, 0.03 cm$^3$. An additional contributor to the discrepancy could be the choice of appropriate manufacturer provided beam quality correction for the Pinpoint chamber, which is provided for standard beam qualities in terms of HVL. However, despite the prohibitively large uncertainty on these estimates, a lower estimate of the dose rate at 140 keV and 2.7 T of $\sim 5 \text{ mGy/s}$ will be used as a design constraint. A final design would then have to be able to discern the temperature rise due to a dose rate of $\sim 5 \text{ mGy/s}$ in air.

The most crucial aspect of the beam is its profile/area, as highlighted by both the air-kerma rate estimates in table 3.1 and the literature review. Based on equation 2.23, the highest energy photons are present in the center of the SR cone before reaching the monochromator, which can be thought of as a band pass filter. The field size would then be expected to decrease as the energy increases. The geometric argument presented in section 2.3.1 also leads one to expect a high beam fall off along the vertical axis and a more uniform beam along the horizontal direction. In a double crystal monochromator the synchrotron operator has some degree of control over the beam shape by modifying the second bent crystal. This requires measuring the beam profile for each beam setup after modifying the crystal. The potential variation in beam profile for the same energy setting of the monochromator would make limiting scatter contributions essential to a calorimeter based dose measurement, as changes
in beam profile would correspond to changes in the degree of scatter and potentially change a detectors response. Limiting scatter contributions is not trivial considering the dominance of scatter for photon interactions in the energy range of interest.

Film has been successfully used to characterize SR beam profiles [7, 8, 107], provided the absorbed dose is within the film’s region of quasi-linear response to dose. Gafchomic™ EBT-3 films (Wilmington, DE) were calibrated using NRC’s Elekta (Stockholm, Sweden) Synergy linac. The Synergy was used to irradiate films using 6 MV photons to several absorbed doses. The calibration curve produced is shown in figure 2.4. The linac’s monitor chamber was used to set the dose delivered and was calibrated using an ion chamber with an absorbed dose calibration traceable to NRC primary standards of absorbed dose, for the same beam quality.

The challenges of performing absolute dose measurements using film in kV beams have been discussed, section 2.2.2, the purpose of calibrating the film used is to verify the region of near linear dose response, which could potentially vary depending on the film batch used. The influence of the energy dependence of film is assumed to be negligible for the relative measurements performed. Using the calibration curve measured, optical density readings between 0.1 and 0.3 AU would imply that the film has an approximately linear response to absorbed dose and can be used as a relative detector in that range.

Figure 3.2 shows a series of horizontal and vertical beam profiles measured at the CLS for different monochromatic beam energies. Films were irradiated with the wiggler operating at 3.7 T. The calibration curve in figure 2.4 was used to correct the optical density measured for non-linearity of the film response, this was minimized by delivering absorbed doses in the region of the calibration curve with minimal deviation from linearity. The curves are normalized with respect to the highest absorbance
reading measured by each film.

The profiles show the decrease in beam size along the vertical direction as the beam energy increases. Additionally, greater uniformity is apparent along the horizontal beam profiles spanning 4 cm. The highest energy beam once again imposes a constraint on the dimensions of the calorimeter, with the need to limit the vertical dimension on the order of a millimeter to reduce the impact of volume averaging.

Stability of the monochromators is essential for a reproducible dose rate. In order to assess the reproducibility of the dose rate, the air-kerma measurements performed using the Exradin® A1SL ion chamber were used. Repeat measurements of the collected charge were found to be reproducible at the 0.1 % level, however larger discrepancies, on the order of 0.5 %, were observed if the monochromators were operated immediately after a beam shutdown or when operated following a change in monochromator energy setting. The potential for changes in monochromator output intensity would require the use of a beam monitor when performing measurements.
Figure 3.2: EBT3 beam profiles for the BMIT-ID 83 - 140 keV monochromatic beams at 3.7 T. The absorbance was corrected using a calibration curve, for films from the same batch, in an MV photon beam. No energy dependence is considered in this energy range. The absorbed dose is plotted relative to the peak dose measured for each film. The horizontal and vertical positions denote the displacement from the film center as shown on the film sample image. Increased noise in the horizontal profiles can be attributed to the smaller axis scale and non-uniformity of the film background over the larger area measured.
3.2 Calorimeter Design Principles

Based on the literature review, attempts at measuring the dose rate due to a synchrotron beam were sensitive to the beam profile. This can be somewhat reduced by employing a collimator. A 25.4 mm thick steel collimator was designed for use during measurements. The collimator shown in figure 3.3 has a 36 mm horizontal by 2 mm vertical slit at its center and figure 3.4 shows this effect.

As discussed in the literature review, water calorimeters provide a direct measurement of the quantity of interest. However, water calorimeters present significant measurement challenges, including complex radio chemistry, convection, encapsulation and low sensitivity. Steep dose gradients found in low energy photon beams [86] and the need for a transportable system for this project are additional constraints. A solid core is desirable and as discussed, graphite is the most common solid material used in absorbed dose calorimetry. Graphite’s similar atomic number to water, no measurable radiochemistry and ease of machining are ideal. However, graphite due to its manufacturing process is inherently inhomogeneous [110].

Aluminum is a non-crystalline elemental and amorphous solid. Pure aluminum is also readily available and machinable. Aluminum has also been used in a number of calorimeter designs, dating back to the 1980s [111], but has been more recently used in radiation therapy applications [112, 113]. Aluminum has an atomic number and physical density higher than water. Despite this, aluminum is elemental, of uniform composition and previous successful demonstrations of its use make it advantageous for this approach. From equation 2.16, the heat capacity of aluminum will determine the measured temperature rise per unit dose.

The heat capacity of aluminum was calculated based on results from 5 different sources [114–118], and determined to be 0.8969(10) J g⁻¹ k⁻¹ based on averaging
the results at room temperature. The uncertainty was determined as the standard uncertainty on the mean, consistent with the approach of Bourgouin [27]. The heat capacity is approximately a fifth that of water at room temperature, resulting in a temperature rise five times as large per unit dose. A diagram of the proposed calorimeter core is shown in figure 3.5.

Figure 3.3: Steel collimator designed for use with the calorimeter prototype. A 36 mm horizontal by 2 mm vertical slit can be seen at its center.
Figure 3.4: The impact of the presence of a 25.4 mm thick steel collimator with a 36 mm horizontal by 2 mm vertical slit at its center, on the vertical beam profile of a 140 keV monochromatic beam generated at 3.7 T. The collimator also serves to truncate the horizontal profiles shown in 3.2.

Figure 3.5: A beam’s eye view diagram of the calorimeter core used for the preliminary design. The field size (36 mm by 2 mm) is defined by the purpose built collimator. The core has dimensions of 40 mm x 0.5 mm perpendicular to the beam, and has a thickness of 0.3 mm. A NTC thermistor is used to measure the temperature rise and aerogel supports are used to fix the core in position.
Core dimensions were optimized to limit the degree of volume averaging in the vertical direction by keeping the vertical core dimension at 0.5 mm. A single NTC thermistor, affixed to the core, will be used to measure the core temperature. Ideally the core would be constructed such that the entire horizontal core dimension would be within the beam, however in the kV range there is potential for significant energy deposition in the thermistor temperature sensor which is composed of high Z material. Thermistor energy deposition becomes increasingly more problematic as the core mass decreases, since the thermistor mass would no longer be negligible relative to the core. By increasing the size of the core laterally the thermistor is shielded by the collimator, making energy deposition in the thermistor negligible. The size of the core in the direction of the beam was kept at 3 mm allowing the thermal mass to be increased, compared to a square core. Increased thermal mass decreases the rate of conductive heat losses away from the core, at the expense of a volume averaging correction in the beam direction. A corresponding increase in core mass also increases the robustness of the calorimeter, allowing it to be more easily transported.

A rectangular shaped core has a high surface area to volume ratio. A high surface area to volume ratio would result in significant heat-loss to the surrounding air. Preliminary calculations showed at least 40% of the radiation induced temperature rise would have been lost to the surrounding air. A 40% reduction in the radiation induced temperature rise due to conductive losses would increase the dose rates required to obtain a measurable, and reproducible temperature rise, limiting the operating range of the calorimeter to higher dose rates.

Primary standard graphite calorimeters for radiation therapy have typically used vacuum gaps to isolate the calorimeter core, the work of Domen and Lamperti being an early example [119]. McEwen et al [120] investigated conduction in a
Figure 3.6: A cross-section of the vacuum enclosure for the preliminary design. The field size (36 mm by 2 mm) is defined by the purpose built collimator and incident from the left, photon tracks are shown in yellow within the enclosure, showing the relatively large size of the vacuum cavity. Any photon tracks interacting with the core have only interacted with either the pure aluminum front window (1.5 mm thick) or the pure aluminum backscatter plate shown in grey. The vacuum pump hose is represented by blue in the image above, an over estimate of its true size meant to highlight that radiation interactions with the pump have no influence on the core.

graphite calorimeter and demonstrated the absence of conductive heat losses to air at pressures below $10^{-4}$ mbar. Such a pressure is readily achievable using a commercial turbomolecular pump. An aluminum-alloy (type 6061) vacuum enclosure was therefore designed and constructed to maintain such a vacuum and minimize the impact of heat conduction.

The vacuum enclosure is shown in figure 3.6, the vessel front window is 1.5 mm thick in the beam direction. A vacuum hose is attached to the rear of the enclosure
and omitted for clarity. To minimize the contribution of scatter from the vessel side walls, the vessel diameter, 80 mm, is significantly larger than the collimated beam. Additionally, although the alloy employed is approximately 96% aluminum by mass, the front window and a rear back scatter plate are constructed from pure aluminum. The beam consequently traverses the core by interacting solely with pure aluminum (the core, front window and back scatter plate). The backscatter plate also shields the core from any photons that back scatter off the non-aluminum vacuum hose, directly in the beam path behind the core.

This approach is very different from conventional solid calorimeter designs, where the core is surrounded by several layers of the same material as the core. For larger beams the jackets would also be irradiated and consequently have a temperature close to the temperature of the core, the reduction in temperature gradients then minimizes heat loss away from the core. By placing the core in a vacuum enclosure the only heat-loss pathway remaining is through the supports and thermistor connecting wires. The small beam size results in a large temperature gradient across the supports, it is then essential to use a material with low thermal conductivity.

Aerogels are low density and low thermal conductivity materials [121]. They have seen use in aerospace applications [122], leading to confidence in their use under vacuum. Aerogel has also been used in probe calorimeters for use in the clinic to minimize heat losses [88]. Aerogel based supports should limit heat losses despite the high temperature gradients across them.

Different aerogel formulations were considered, including both silica and polyimide-based materials. The aerogels were assessed based on material properties and ease of machinability, as the contact area of the support with both the core and enclosure is directly proportional to the heat lost. Despite the superior performance of silica
aerogel in the simulations, the material proved difficult to machine to the small
dimensions required, and so the lowest density polyimide aerogel was chosen. X-116
Airloy (Aerogel Technologies LLC, Boston, MA) is used with a density of 0.09 g cm$^{-3}$
and a thermal conductivity of 29 mW m$^{-1}$K$^{-1}$ in ambient air.

To assess the feasibility of the novel design, the contribution of the vacuum
vessel to the dose absorbed by the aluminum core needs to be quantitatively assessed.
Conductive heat losses need to be characterized as well as they determine, in addition
to the specific heat capacity of the core, the temperature rise per unit dose absorbed
by the core. Dose to the aluminum core in air, in the absence of the vessel and other
non-core components, while not the ultimate quantity of interest, serves as an intuitive
way to assess the feasibility of the design. The dose to the aluminum core in air can
be expressed as:

$$D_{\text{core,air}} = c_{\text{Al}} \Delta T k_{\text{vessel}} k_{ht} \frac{A_{\text{core}}}{A_{\text{irrad}}}$$  (3.1)

Where, $k_{\text{vessel}}$ is a correction for the influence of the vessel enclosure and any other
non-core components on the absorbed dose to the core. $k_{ht}$ denotes a heat transfer
correction to account for conductive heat losses that would reduce the measured
temperature rise. $\frac{A_{\text{core}}}{A_{\text{irrad}}}$ corrects for the portion of the aluminum core that, due to
the collimation discussed, is not directly irradiated by the beam. $c_{\text{Al}}$ and $\Delta T$ denote
the measured temperature rise and the specific heat capacity of aluminum at room
temperature respectively.
3.3 The Heat Transfer Correction, $k_{ht}$

3.3.1 Introduction

To quantitatively assess the heat transfer correction a thermal simulation of the calorimeter was performed. $k_{ht}$ corrects the temperature measured during an irradiation for heat losses and can be defined as:

$$k_{ht} = \frac{\Delta T_{noheatloss}}{\Delta T_{heatloss}}$$

Heat loss occurs through three mechanisms; convection, radiative heat loss and conduction. In the case of a solid calorimeter core in a vacuum enclosure heat losses due to convection are negligible. Likewise, due to the small temperature rises measured, on the order of 10 mK, radiative heat losses can be neglected. Conduction is then the only heat loss mechanism to be considered when calculating $k_{ht}$.

A typical calorimeter temperature trace is shown in figure 3.7. To determine the radiation induced temperature rise pre- and post-irradiation linear fits are applied to the temperature trace. The fits are then extrapolated to the irradiation midpoint. This procedure is essentially a rudimentary heat loss correction, and is based on the assumption that the heat loss correction is proportional to the temperature difference between two bodies. If a proportionality constant relates the heat loss correction to the temperature difference, over the measurement time scale, it can be approximated by a linear fit. Such an approximation is valid for cores with large thermal masses, low temperature gradients and near ideal thermal isolation, typically the case for most calorimeter designs in use today. In the case of a calorimeter with a small core and significant temperature gradients an additional correction is required $k_{ht}$, to correct
the temperature rise determined using the linear fits to the true temperature rise in
the absence of heat losses.

Heat transport due to conduction only can be described by the following partial
differential equation, PDE, [123]:

\[
\rho c \frac{\partial T}{\partial t} + \nabla (-k \cdot \nabla T) = \rho \dot{D}
\]  

(3.3)

Where, \( \rho c \) denote the density and specific heat as a function of position respectively.
\( k \) the thermal conductivity and \( T \) the temperature as a function of time and position.
Equation 3.3 can be used to derive the temperature in the absence of conductive heat
losses by setting \( k = 0 \) and integrating over the irradiation time \( \Delta t \). Equation 3.2 can
then be rewritten as :

Figure 3.7: A typical calorimeter temperature trace. The pre- and post-irradiation
temperature fits are shown and extrapolated to the irradiation midpoint. The differ-
ence between the extrapolated temperature fits at the irradiation midpoint defines the
uncorrected radiation induced temperature rise.
Equation 3.4 shows that $k_{ht}$ is independent of dose rate, but will depend on the material properties $\rho c$, constant over the small temperature ranges involved in calorimetry, and crucially the irradiation time. For the calorimeter, a single $k_{ht}$ correction can then be used irrespective of beam dose rate, and energy, provided the irradiation time is fixed.

### 3.3.2 The Finite Element Method

To solve equation 3.3 for the temperature, COMSOL® Multiphysics software [124] was used. COMSOL® employs finite element modeling (FEM), a numerical technique to solve PDEs. Solving the PDE allows the temperature rise of the calorimeter to be determined and the simulation of conductive heat losses, as a function of time.

FEM relies on discretizing the PDE, in the case of modeling the conduction in the calorimeter a single dependent variable, the temperature, needs to be considered. The PDE is solved over a discretized solution space, i.e a discrete geometry at discrete moments in time. The discrete geometry is composed of volume elements forming a mesh. The size of the mesh, i.e the total number of mesh elements per unit volume, directly influences the accuracy of the model. In the limit that the mesh element size approaches zero the problem is no longer discretized and approaches the true PDE solution. A smaller element size implies more elements to encompass the geometry of interest and consequently increases the number of numerical calculations to be performed, resulting in longer computation times. The error bounds provided by the FEM are typically orders of magnitude smaller than the uncertainty introduced due
to the inputs to the simulation including; specific heat capacities, density and physical dimensions of the different components comprising the simulation geometry.

COMSOL® calculated $k_{ht}$ values have been previously validated with experiment [125] and used for different calorimeter designs [27, 88, 125]. A simplified version of the calorimeter used for this project was modeled using a custom MATLAB [126] based script, to solve the heat equation using the FEM and was found to agree with a COMSOL® produced solution for the same geometry at the 0.1 % level. The agreement between the custom MATLAB based FEM implementation and COMSOL® for the simplified geometry lends confidence in the use of COMSOL® for the numerical simulations in this work.

To perform a COMSOL® simulation, the relevant system of PDEs is chosen or defined by the user. For this project only equation 3.3 is relevant. A simulation geometry is then defined including all heat sources and boundary conditions. Different stages of the modeling process are shown in figure 3.8.

To model the calorimeter, only the core and attached components are considered. The point of contact of the aerogel supports and the thermistor wire with the aluminum vacuum vessel are taken as boundary conditions and set to a fixed temperature that remains unchanged throughout the simulation. The core itself is used as a heat source.

Photon beams will deposit energy non-uniformly, as they traverse the 3 mm thick core. A characteristic photon depth dose curve results in a corresponding temperature distribution within the core. Fortunately given the high thermal conductivity of aluminum, the temperature distribution equilibrates throughout the aluminum core on a time scale of 0.2 s and has a negligible impact on the simulation result. Similar assumptions are made when modeling graphite calorimeters [89], which supports our conclusion considering the thermal conductivity of aluminum is twice that of graphite.
Figure 3.8: Steps to perform a FEM simulation using COMSOL. The PDEs governing the physics to be simulated are selected, equation 3.3. Boundary conditions are also defined for the calorimeter: the ends of the aerogel supports and thermistor wires (attached to the vacuum vessel) are used as boundary conditions and fixed at room temperature. 1. An accurate model of the geometry to be simulated is then constructed using the computer aided design interface, note the detail in the inset wire frame image showing the inner components of the thermistor. The aerogel supports are shown in yellow, and the core in grey. 2. A mesh is constructed, this descriptizes the geometry and defines the locations where the temperature will be calculated, note how the variable mesh used is denser at the interface between dissimilar materials to maintain the accuracy of the result. 3. A typical simulation result, showing a heat map during irradiation.
Figure 3.9: A typical calorimeter temperature trace is shown in the top figure. The irradiation starts at 10 s and ends at 25 s. The bottom figure shows the solution time steps taken by the FEM solver, note the decrease in the solution time step at the beginning and end of the irradiation.

To reduce computation time, simulations are typically performed in two dimensions, to take advantage of the axial symmetry of many calorimeter designs [27, 88, 125]. The synchrotron calorimeter core assembly is not axially symmetric. To overcome this, the discretization of the solution in time was allowed to vary, by making the solution time step $\propto \frac{1}{\Delta T}$, i.e. the solution time step decreases when large changes in temperature are detected. To ensure that the solution time step is not large enough to miss the beginning or end of an irradiation, the COMSOL® model was forced to take small solution time steps, on the order of 0.01 ms, in the vicinity of the beginning and end of an irradiation. For example in figure 3.9, the solution time step ranges from 0.01 ms at the start and end of an irradiation to 3.5 s in the regions of near constant $\frac{d^2T}{dt^2}$. 
Varying the solution time step is a common method to reduce FEM simulation time and does not sacrifice the accuracy of the result, provided any external changes to the simulation space such as the switching on of a heat source midway through a simulation are accounted for. Computational time can then be reduced by several orders of magnitude. The variation of the time step was tested by comparing the results of a simplified geometric model of the calorimeter with and without varying the time step, the results being found to be identical.

3.3.3 Results

Preliminary thermal simulations, figure 3.10, showed that the copper wires of the thermistor temperature sensor resulted in significant conductive heat losses. Despite the small wire diameter, 0.06 mm (44 Gauge), the large thermal conductivity relative to the other components in contact with the calorimeter core provided a substantial heat-loss pathway. A nickel-wire thermistor was chosen, extensively used in industrial processes for their corrosion resistance, with a thermal conductivity approximately 20% that of copper [127], the most commonly used material for thermistor wires. Conductive heat losses are significantly reduced with an overall reduction in $k_{ht}$ from 1.08 to 1.03.

An additional concern is the thermal contact between the thermistor and aluminum core. Thermistors are usually embedded within larger cores, typical of most calorimeter designs. However, given the small size of the aluminum core, the thermistor was attached to the surface of the core and encased in a thermally conductive adhesive. By employing a nickel based adhesive, adequate thermal contact is maintained between the thermistor and the aluminum core. In figure 3.10, adequate thermal contact is indicated by the temperature traces of both the core and thermistor being parallel.
Figure 3.10: A preliminary simulation showing the temperature traces of each of the main core components. The heat source is switched on at 0 s and is switched off at 15 s, to simulate a typical irradiation. The plot illustrates the efficacy of aerogel as an insulator in addition to highlighting the heat loss pathway through the thermistor wires.

Post-irradiation.

Polyimide aerogel supports were chosen for the design. A sensitivity study was performed for different values of polyimide aerogel thermal conductivity (0.003 - 0.029 W/(m.K)). By keeping all thermal simulation properties unchanged and only varying the aerogel thermal conductivity, $k_{ht}$ values could be generated for each value of thermal conductivity used. The largest recorded change in $k_{ht}$ was on the order of 0.1 %.

Direct energy deposition in the thermistor is a concern, and the heat sharing
that occurs immediately after an irradiation between the thermistor and the core could potentially allow the radiation induced temperature rise to be overestimated [85, 107]. An attempt to qualitatively model the impact of direct thermistor heating is shown in figure 3.11. Post-irradiation the thermistor, which is in thermal contact with the more massive lower temperature core, loses its excess temperature to the core and wires. This is signified by the rapid fall-off of the thermistor temperature post-irradiation, an equilibrium is reached when the thermistor trace is parallel to the core temperature trace. This has been overcome in other investigations by performing the post-irradiation fits at a delayed time after the end of an irradiation. The collimator

![Graph showing temperature change](image)

**Figure 3.11:** *A simulation showing the impact of direct thermistor heating on the post-irradiation temperature trace. Both the thermistor and core are modeled as heat sources. The high Z thermistor results in increased energy deposition relative to the core when irradiated directly, this energy deposition results in a larger temperature rise relative to the core and is estimated using EGSnrc. Given the small mass of the thermistor, excess heat is quickly lost to the more massive core, which is at a lower temperature. At approximately 2 s post-irradiation the impact of the excess thermistor temperature is lost.*
**Figure 3.12:** A simulation result illustrating the procedure for calculating the heat loss correction $k_{ht}$. The heat source is switched on at 10 s. Two core temperature traces show the simulation with conduction switched on in red and switched off in blue. A linear fit is performed 4 s after the end of an irradiation, and extrapolated to the irradiation mid-point, 17.5 s. The temperature for both simulations is shown after extrapolation at 17.5 s, note that the post-irradiation temperature is constant for the simulation with the conduction switched off. A ratio of the two temperatures defines the heat loss correction, $k_{ht}$.

used in this work is intended to minimize this effect by shielding the thermistor.

Figure 3.12, shows the procedure to calculate $k_{ht}$. A simulation is performed where the calorimeter core is heated for 15 s, the post-irradiation temperature trace is linearly fitted and extrapolated to the irradiation mid-point, 17.5 s in the figure, resulting in a measure of $\Delta T_{\text{heatloss}}$. Based on the preceding discussion on the potential for non-linearity immediately following an irradiation, due to heat sharing affects, the fit is applied 4 s after the end of the irradiation. An identical simulation is then performed with thermal conduction switched off, and the maximum temperature then denotes $\Delta T_{\text{noheatloss}}$ in equation 3.2. Based on figure 3.12 a heat loss correction of
1.030 ± 0.002 is determined by applying equation 3.2. The derived value of $k_{ht}$, was based on a COMSOL® simulation where all geometric dimensions and masses were based on real measurements of the calorimeter prototype. An identical off-set of 4 s will be used during measurements with the calorimeter in the synchrotron beam to determine the radiation induced temperature rise during experiment. Whilst $k_{ht}$ is approximately 10 times greater than for conventional water calorimeters it is the same order of magnitude as graphite calorimeters reported in the literature [27].

### 3.4 The Radiation Transport Correction, $k_{vessel}$

#### 3.4.1 Introduction

The purpose of the radiation transport correction is to account for the effect of the vessel on the dose deposited in the pure aluminum core. The feasibility of the detector design relies on the ability to accurately model the radiation interactions in the vessel, that contribute to the absorbed dose in the core. Photon interactions that result in scattering off the vessel’s inner walls and the different components surrounding the aluminum core can potentially increase the dose deposited. If the impact is large a detailed geometry would be required to accurately assess it, resulting in additional uncertainty contributions. The potential for back-scattering from the vacuum pump attachment, at the rear of the enclosure is an additional concern. The photon beam’s attenuation through the aluminum front window must also be quantitatively assessed, to ensure that the absorbed dose and resulting temperature signal is still measurable. $k_{vessel}$ can be further divided into three components:

- $k_{attn}$, an attenuation correction for the reduction in the number photons reaching the core due to the presence of the 1.5 mm thick pure aluminum front window.
\( k_{scatter} \), a scatter correction for the increase in the number of photons reaching the core due to scattering from any geometries in the simulation, this includes the thermistor, nickel paste, vessel walls, back-scatter plate and aerogel supports.

\( k_{col} \), the \( k_{vessel} \) correction assumes perfect collimation of a parallel beam and that the beam size is 36 mm, matching the collimator. \( k_{col} \) corrects for the energy deposited outside the 36 mm horizontal dimension defined by the collimator and is a measure of the efficacy of the collimation used.

Then \( k_{vessel} \) can be represented as:

\[
k_{vessel} = k_{scatter} \cdot k_{attn} \cdot k_{col}
\]  

\[ (3.5) \]

3.4.2 The Monte Carlo Method

The Monte Carlo, MC, method for the simulation of radiation transport uses knowledge of the microscopic probability distributions governing radiation interaction probabilities with matter [128]. A particle traversing a medium can potentially be scattered or absorbed and create secondary particles in the process. The calculation of the energy deposition, random trajectories and energies of interacting particles and their progeny is the ultimate goal of a radiation transport code [128]. This is achieved by modeling individual particle interactions and recording/scoring the quantity of interest, for example the absorbed dose in a geometry.

To demonstrate the MC method a monoenergetic photon pencil beam will be considered, traversing an infinite volume composed of a uniform material. For this demonstration we will limit the photon to interacting through only the Compton and Photoelectric effects. The total interaction cross-section can then be expressed as a
sum of the Compton and Photoelectric cross-sections, which depend on the elemental composition and density of the medium:

$$\sigma_{total} = \sigma_{Photoelectric} + \sigma_{Compton} \quad (3.6)$$

To simulate the photon traversing the medium in our example, the distance to an interaction needs to be determined. Based on the exponential attenuation of photons through matter the distance to an interaction can be defined as:

$$N = N_0 e^{-\sigma_{total}d}$$

$$1 - \frac{N_0 - N}{N} = e^{-\sigma_{total}d} \quad (3.7)$$

$$\frac{-1}{\sigma_{total}} \ln[R] = d$$

Where $N_0$ and $N$ denote the incident number of photons before and after traversing a distance $d$ in the medium. The quotient, $1 - \frac{N_0 - N}{N}$, has been replaced by a uniform random number between $[0,1]$ denoted by $R$. To perform a MC simulation a random number is generated for each photon simulated, equation 3.7 is then used to calculate the position at which an interaction occurs.

The next step in our simple simulation is to determine the type of interaction that occurs. Another random number, $R_2$ between $[0,1]$, is generated and the interaction that occurs is determined according to:

$$R_2 \leq \frac{\sigma_{Photoelectric}}{\sigma_{total}} \Rightarrow \text{Photoelectric interaction}$$

$$R_2 > \frac{\sigma_{Photoelectric}}{\sigma_{total}} \Rightarrow \text{Compton interaction} \quad (3.8)$$
This process would be repeated for a large number of histories, typical simulations model more than $10^9$ particles. If the quantity of interest is the energy deposited, then an interaction cross-section differential in energy would be sampled to determine the energy lost by the photon to the medium, for each interaction type.

As the number of simulated particles, often referred to as histories, increases the variance of the quantity scored decreases. While a decrease in the variance implies a decrease in the uncertainty of MC as a numerical method, it is however not the only contributor to the overall simulation uncertainty. The total uncertainty would have to include contributions from the inputs to the simulation, such as microscopic interaction cross-section data, and both the accuracy of the geometry and particle source simulated. The example shown is greatly over simplified but essentially gives the underlying principle of all MC based radiation transport codes.

EGSnrc, Electron Gamma Shower NRC, is an open source MC software toolkit for the simulation of electron and photon transport through matter, for energies in the 1 keV to 10 GeV range [129]. EGSnrc is widely used in medical physics and has been extensively validated for general particle transport [130–132] and for photons in the keV range [133–135]. One disadvantage of the EGSnrc system is that it currently does not model the effect of photon polarization, an important property of SR that will impact the photon interactions with matter. Despite this limitation, EGSnrc was chosen to conduct the radiation transport simulations to leverage the variance reduction techniques in existing applications, which significantly reduce simulation time, while preserving the accuracy of the result. The choice of EGSnrc will be validated by comparing results to simulations generated with the Geant4 software toolkit, a widely used MC toolkit for particle physics applications, that accounts for the impact of photon polarization [136].
An EGSnrc simulation can be separated into two parts: the underlying radiation transport common to all EGSnrc user applications, such as Cavity used in this work, and a series of user inputs defined in an .egsinp file. The input file includes a definition of all geometries to be modeled, and a description of their elemental composition. The geometry is created using a built in library of several geometric shapes, egs++, with the ability to perform boolean combinations of them to reproduce a wide array of geometries. To simulate interactions with the geometry, in addition to elemental composition, the density, mean excitation potential and density correction must be provided. Much of this data is readily available for commonly used material within EGSnrc, nevertheless material data can be readily created by the user for additional media.

A source of particles must also be defined by selecting the source shape, particle type, energy and direction. A number of predefined sources facilitate this procedure. The quantity to be scored must also be provided, of interest for this project is the dose deposited in different geometry components. Transport parameters such as the choice of cross-sections and which interactions to model can be defined as well, in addition to any user selected variance reduction techniques.

Of the transport parameters used of most interest in this work are the energy cut-off values. Energy cut-off values determine the energy at which a particle history is terminated, i.e. once a particles energy falls below the cut-off value the particle’s energy is deposited at its current location and it is no longer simulated. This has the largest impact on simulation time, increasing the electron (ECUT) and photon (PCUT) cut-off values exponentially decrease simulation time, but potentially at the expense of simulation accuracy. All simulation results quoted in this work were performed with PCUT and ECUT values of 1 keV and 512 keV respectively, (in EGSnrc the
rest mass of an electron 511 keV is included when defining ECUT) the lowest energy modeled by EGSnrc. For reference a 1 keV electron has a range of less than 1 µm in aluminum and water.

To perform simulations with sufficiently low energy cut-off values while maintaining practical computational times, variance reduction techniques are used. Consider a simple simulation geometry, where the goal is to simulate the energy deposited due to a photon beam in a small volume of water within a larger water phantom. If no variance reduction is used, EGSnrc will follow every electron generated by the interacting photons, including their progeny, until all particles reach an energy below the cut-off value. The simulation time would be significantly reduced (particularly if the simulation geometry is large relative to the scoring volume) if particles generated that do not have enough energy to reach the scoring volume are discarded. This can be achieved in the EGSnrc Cavity application by applying a range based variance reduction method called Russian Roulette for electrons [137], which has the greatest impact on simulation time, given the large number of interactions modeled per unit length.

For every charged particle generated during a simulation the particle’s equivalent range is calculated, in the medium with the lowest stopping power. If the perpendicular distance between the particle and the scoring volume is larger than the particles range, and the particle does not have sufficient energy to move to the next geometry, then it is discarded with a probability set by the user. The minority of particles that survive are assigned a greater statistical weight, this means that if the user assigned probability for discarding the electrons is too high the surviving particles, with greater statistical weight, will increase the variance in the simulation result. Being a true variance reduction technique, there is no influence on the accuracy of the simulation
that would not be reflected in a change in the variance of the result. Setting the probability of discarding the electrons too high is typically a concern for higher energy simulations. At higher energies, the probability that an electron traversing a medium will release a bremsstrahlung photon (with a significantly greater range than the electron) that could deposit energy in the scoring volume is non-negligible. This is a minor concern in kV beams, since the number of bremsstrahlung photons released by the low energy secondary electrons is negligible. For reference the radiative yield of a 150 keV electron in pure aluminum (the fraction of its kinetic energy converted to bremsstrahlung photons in coming to rest), is 0.2 %.

Several factors impact the accuracy of a MC simulation. The variance in the result is one indication of its accuracy, however that can be arbitrarily decreased by increasing the number of simulation histories. In addition, the MC transport parameters chosen by the user, the interaction cross-sections used, the accuracy with which the different geometries and their material compositions are modeled, and the accuracy with which the radiation source is modeled all impact the overall accuracy of a simulation. The MC transport parameters used throughout this work are shown in table 3.2.

### 3.4.3 Results

The calorimeter was simulated using the EGSnrc cavity application. A photon source is modeled as described in the appendix A with the photons originating 55 m behind the steel collimator. The photons are then propagated through the steel collimator (36 mm x 2 mm). The simulated geometry is shown in figure 3.13. The complete vessel is simulated, being composed of aluminum 6061 alloy, with the pure aluminum front window and back-scatter plate shown. At the same horizontal position of the core,
**Table 3.2:** Default MC transport parameters used for EGSnrc simulations.

<table>
<thead>
<tr>
<th>Transport parameter</th>
<th>Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photon cross sections</td>
<td>mcdf-xcom</td>
</tr>
<tr>
<td>Brems cross sections</td>
<td>NRC</td>
</tr>
<tr>
<td>Brems angular sampling</td>
<td>KM</td>
</tr>
<tr>
<td>Electron impact ionization</td>
<td>penelope</td>
</tr>
<tr>
<td>Rayleigh scattering</td>
<td>On</td>
</tr>
<tr>
<td>Spin effects</td>
<td>On</td>
</tr>
<tr>
<td>Bound Compton scattering</td>
<td>norej</td>
</tr>
<tr>
<td>Radiative Compton corrections</td>
<td>Off</td>
</tr>
<tr>
<td>Atomic relaxations</td>
<td>On</td>
</tr>
<tr>
<td>Pair angular sampling</td>
<td>simple</td>
</tr>
<tr>
<td>Triplet production</td>
<td>Off</td>
</tr>
<tr>
<td>PE angular sampling</td>
<td>On</td>
</tr>
<tr>
<td>Photonuclear attenuation</td>
<td>Off</td>
</tr>
<tr>
<td>Photonuclear cross sections</td>
<td>default</td>
</tr>
<tr>
<td>Boundary crossing algorithm</td>
<td>exact</td>
</tr>
<tr>
<td>Skin depth for BCA</td>
<td>3</td>
</tr>
<tr>
<td>Electron-step algorithm</td>
<td>PRESTA-II</td>
</tr>
<tr>
<td>Rayleigh scattering</td>
<td>On</td>
</tr>
</tbody>
</table>

Steel cylinders are used to model the impact of vacuum feed-throughs that allow the thermistor wires to be connected to equipment outside the vacuum vessel. The vessel side walls are well outside the beam and consequently the accuracy of the simulated feed-throughs becomes less important to the accuracy of the overall simulation.

The thermistor is modeled as a nickel oxide chip, to allow the energy deposition in the thermistor to be assessed. The nickel paste used to encase the thermistor
**Figure 3.13:** The EGSnrc model of the calorimeter. Different cutting planes are used to highlight the internal details. Aluminum 6061 alloy is shown in red. The vacuum pump attachment is modeled as steel, shown in green. In the center image the back-scatter plate is removed for clarity. The beam enters the calorimeter through the pure aluminum front window, shown in blue in the left most image, the diameter of the front window is 4 mm larger than the collimated source.

and attach it to the core was also modeled in addition to the low density polyimide aerogel supports. The accuracy with which the different geometries and their material compositions are modeled contributes to the overall uncertainty of the MC simulation. Ultimately the goal of the simulation is to score the dose deposited in the pure aluminum core to derive $k_{vessel}$.

To assess the contribution of the different geometry components to $k_{scatter}$, the change in dose deposited in the aluminum core was assessed with and without their presence for the different beam energies considered. The small size of the collimated beam, 36 mm x 2 mm, meant that the contribution of scatter from the low density aerogel, nickel paste and thermistor was negligible. The simulations also confirmed that the contributions of scatter from the vacuum vessel side walls and the aluminum back scatter plate was negligible for all energies of interest. This can be attributed to
**Beam**

![Diagram of beam](image)

$k_{\text{attn}} = \frac{D_b}{D_a}$

$k_{\text{scatter}} = \frac{D_c}{D_b}$

$k_{\text{col}} = \frac{D_d \cdot A_{\text{irrad}}}{D_c \cdot A_{\text{core}}} = \frac{D_d \cdot 36 \text{ [mm]}}{D_c \cdot 40 \text{ [mm]}}$

**Figure 3.14:** A series of EGSnrc simulations showing how the different components of $k_{\text{vessel}}$ are derived. $D_a$, denotes the dose scored to the calorimeter core in simulation a. (a) The full calorimeter core including all components are simulated. (b) Identical to a but has the front window removed. (c) Only the core is modeled in the same position as in simulation a. (d) The truncated core is modeled matching a perfectly collimated beam.

the significantly larger diameter of the vacuum vessel, 80 mm, relative to the beam size. Additionally, the small area subtended by the calorimeter relative to the back scatter plate results in a negligible back-scatter contribution, even if a 2 cm steel plate is placed behind the back scatter plate, implying that the vacuum pump attachment in the rear of the calorimeter has no effect. The only contributor to the absorbed dose in the core is the vessel front window and the dimensions of the core itself relative to the beam size, i.e $k_{\text{scatter}} = 1.000$. The series of MC simulations illustrated in figure 3.14 were used to calculate the components of $k_{\text{vessel}}$ in equation 3.5.

When simulating $k_{\text{col}}$ in figure 3.14, one must multiply the result by the ratio of
Table 3.3: EGSnrc calculated $k_{vessel}$ corrections and components

<table>
<thead>
<tr>
<th>E (keV)</th>
<th>$k_{attn}$</th>
<th>$k_{scatter}$</th>
<th>$k_{col}$</th>
<th>$k_{vessel}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>140</td>
<td>1.058</td>
<td>1.000</td>
<td>0.976</td>
<td>1.033</td>
</tr>
<tr>
<td>115</td>
<td>1.064</td>
<td>1.000</td>
<td>0.977</td>
<td>1.040</td>
</tr>
<tr>
<td>100</td>
<td>1.069</td>
<td>1.000</td>
<td>0.977</td>
<td>1.044</td>
</tr>
<tr>
<td>83</td>
<td>1.081</td>
<td>1.000</td>
<td>0.977</td>
<td>1.055</td>
</tr>
</tbody>
</table>

the core masses simulated, to convert the scored dose to the energy deposited. This is equivalent to multiplying by the ratio of the irradiated area and the core area. Decoupling the correction from its dependence on the mass irradiated, allows the efficacy of the collimator to be assessed by measuring the energy deposited in the area not directly irradiated by the beam. If the mass irradiated was not decoupled from the correction in this way, then a perfectly collimated beam with no energy deposition due to indirect irradiation of the core would result in a $k_{col}$ correction that is equal to 1.11, the ratio of the collimator area to the core area, as opposed to unity. The dose to the 36 mm portion defined by the collimator is then recovered by multiplying by $\frac{A_{core}}{A_{irrad}}$ in equation 3.1. The results are summarized in table 3.3.

Despite the natural collimation of the synchrotron beam, the divergence results in a 2.3% correction to the absorbed dose. This is a product of the distance between the core and collimator. The simulation used a collimator core distance of greater than 1 m, in an attempt to limit collimator scatter. The reasoning being that $k_{col}$ would be less sensitive to variations in the experimental setup as opposed to the collimator scatter, which could potentially irradiate the calorimeter side walls or thermistor. Despite the relatively large $k_{attn}$ correction, it is important to note that the simulation only involves calculating the attenuation of a monochromatic beam through pure aluminum of accurately known thickness, which is expected to have a low overall
uncertainty.

While the thermistor and nickel paste contribute a negligible amount of scatter to the core, the dose deposited in both those geometries must be assessed. Energy deposition in both the thermistor and nickel paste attached to the core would increase their temperature, and have an impact on the accuracy of the $k_{ht}$ correction. The energy deposited in the nickel paste is summarized in table 3.4, the energy deposited in the thermistor was less than 0.1% of the total energy deposited in the core for all energies.

The preceding results justify that the geometry is behaving as expected, minimal scatter contribution, and photon interactions are limited to the core and aluminum front window. For completeness, simulations were repeated with all aluminum alloy components replaced with pure aluminum, and resulted in no difference in the dose deposited in the core.

The material composition of both the vessel front window and core are a potential source of uncertainty in the simulation result. Pure aluminum typically forms an aluminum oxide layer when exposed to air, the layer is on the order of 4 nm thick and prevents further oxidation of the remaining aluminum [138]. A photon incident on the vessel front window would traverse, on average, 4 aluminum oxide layers (either

<table>
<thead>
<tr>
<th>E (keV)</th>
<th>% Energy Deposited in Nickel Paste</th>
</tr>
</thead>
<tbody>
<tr>
<td>140</td>
<td>0.20</td>
</tr>
<tr>
<td>115</td>
<td>0.14</td>
</tr>
<tr>
<td>100</td>
<td>0.12</td>
</tr>
<tr>
<td>83</td>
<td>0.13</td>
</tr>
</tbody>
</table>
side of the front window and the entrance/exit surface of the core). A 16 nm thick aluminum oxide layer is expected to have a negligible impact on the simulation result. To validate this assumption a 50 nm aluminum oxide layer was simulated at the front and rear surface of the calorimeter core. As predicted the oxide layer (despite being more than 3 times larger than expected) had no impact on the simulation result.

The interaction cross-sections determine both the probability of and type of photon interaction that takes place during a simulation. EGSnrc allows the choice of photon interaction cross-sections between NIST xcom [139] and the Livermore photon data library epdl [140] cross-sections. Both cross-section data sets are widely used for photons in the keV range. The results in table 3.3 were reproduced using both interaction cross-section data sets producing $k_{\text{vessel}}$ values within 0.1 % for all energies.

The cross-sections included with EGSnrc do not model polarization, and there is no independent way to validate the condensed history implementation used to model the energy deposition of secondary electrons within EGSnrc. For the photon energies of interest, differences in calculation of the correction factors in table 3.3 are not expected for different MC codes, however this assumption must be validated.

### 3.4.4 GEANT4 Based Validation

Repeating the calculations to derive the correction factors in table 3.3 using a different MC code allows the influence of polarization on the simulations to be determined. In addition, the secondary electron multiple scattering theory implementation can be validated [141]. Interaction cross-sections for the photon interactions of interest in this work are shown in table 3.5, for both polarized and un-polarized photons. The additional azimuthal dependence of the interaction cross-sections for polarized photons
Table 3.5: Polarized and unpolarized photon differential cross-sections. The additional azimuthal dependence of the cross-sections in the case of polarized photons is highlighted. In the formulae \( r_0 \) denotes the classical electron radius, \( \theta_e / \theta \) the polar angle of the photoelectron and photon respectively, similarly \( \phi_e / \phi \) denotes the azimuthal angles, \( F(q, Z) \) the atomic form factor, \( q \) the momentum transfer, \( Z \) the atomic number, \( k \) the initial or final wave number, \( \alpha \) the fine structure constant, \( \hbar \) the reduced Planck’s constant, \( c \) the speed of light, \( a_0 \) the hydrogen Bohr radius, \( \nu_e \) the photo-electron velocity and \( m_0 \) the electron rest mass [96].

<table>
<thead>
<tr>
<th>Interaction</th>
<th>Cross-section</th>
<th>Unpolarized</th>
<th>Polarized</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rayleigh Scattering</td>
<td>( \frac{d\sigma_R}{d\Omega} )</td>
<td>( \frac{r_0^2}{2} (1 + \cos^2 \theta) F^2(q, Z) )</td>
<td>( \frac{r_0^2}{2} (1 - \sin^2 \theta \cos^2 \phi) F^2(q, Z) )</td>
</tr>
<tr>
<td>Compton Scattering</td>
<td>( \frac{d\sigma_{KN}}{d\Omega} )</td>
<td>( \frac{r_0^2}{2} \left( \frac{k_f}{k_i} \right)^2 \left( \frac{k_i}{k_f} + \frac{k_l}{k_f} - \sin^2 \theta \right) )</td>
<td>( \frac{r_0^2}{2} \left( \frac{k_l}{k_i} \right)^2 \left( \frac{k_i}{k_f} + \frac{k_l}{k_f} - 2 \sin^2 \theta \cos^2 \phi \right) )</td>
</tr>
<tr>
<td>Photoelectric Interaction</td>
<td>( \frac{d\sigma_{PE}}{d\Omega} )</td>
<td>( 16\alpha \left( \frac{\hbar}{m_0} \right) \frac{Z^5}{c k_i (k_e a_0)^7} \left( 1 - \frac{\sin^2 \theta_e}{\cos \theta_e} \right)^7 )</td>
<td>( 32\alpha \left( \frac{\hbar}{m_0} \right) \frac{Z^5}{c k_i (k_e a_0)^7} \left( \frac{\sin^2 \theta_e \cos^2 \phi_e}{\cos \theta_e} \right)^7 )</td>
</tr>
</tbody>
</table>

is highlighted in table 3.5. The azimuthal dependence relative to the direction of beam propagation could potentially increase the scatter component of \( k_{\text{vessel}} \) and motivated this investigation. Allowing the user to re-generate the geometry and particularly the source in a different code will also serve to validate the new source model created in EGSnrc.

GEANT4 was used to perform the simulations, including modeling polarization effects [136]. GEANT4 is a widely used MC code for both particle and medical physics applications. The synchrotron source was defined in GEANT4 using the same procedure outlined for the EGSnrc based simulations. However, there is no need to use an analog for the EGS\_collimated source in GEANT4 as the photon vectors were explicitly defined, with no MC weighting added. Defining the source in this way would serve to validate that the EGSnrc MC weighting, applied by the EGS\_collimated
source, does not affect the result.

The geometry and all materials were recreated in GEANT4 using the appropriate geometry methods and material definition files. G4EmLivermorePolarizedPhysics cross-sections were used for all simulations and production cuts set to 3.7 \( \mu m \) (a particle with a range below 3.7 \( \mu m \) would not be produced, this corresponds to approximately 20 keV for an electron in aluminum) to reduce simulation time. Simulations in figure 3.14 were repeated for all beam energies. Linearly polarized photons, were generated and simulations performed alternately with polarization along both perpendicular axis, to the direction of beam propagation.

All calculated \( k_{vessel} \) values agreed within 0.1 % for all energies between simulations with polarity switched on and off. This can be attributed to the negligible contribution of scatter from the vessel to the absorbed dose in the core. Additionally, GEANT4 calculated \( k_{vessel} \) values agreed with the EGSnrc values within 0.1 %. These results serve to validate the use of EGSnrc to calculate \( k_{vessel} \) and the assumption that the EGSnrc MC weighting applied by the EGS_collimated source does not affect the result.

Based on the preceding discussion the \( k_{vessel} \) calculation is primarily composed of modeling the attenuation of a monochromatic beam of known energy through a pure aluminum media. As a result, the contribution to the overall uncertainty due to the incident beam spectra is eliminated. Additionally, the highest energy photon beam results in an electron range of less than 0.1 mm in aluminum, and a radiative yield of less than 0.2 %, limiting the contribution of electron transport to the overall uncertainty. Consequently, the photon interaction cross-sections become the main contributor to the overall simulation uncertainty. Based on the recommendations of The International Commission On Radiation Units and Measurements’, ICRU,
3.5 Detector Construction

3.5.1 Aluminum Vacuum Vessel

The vacuum vessel was fabricated from a single piece of aluminum 6061 alloy by NRC Design and Fabrication Services. A computer numerical control, CNC, lathe was used to machine the vessel which is comprised of two main parts: the front window and the vessel itself.

Figure 3.15, shows the components of the vacuum vessel. The front window is machined such that a pure aluminum cylindrical insert, 1.5 ± 0.005 mm thick and 4 cm in diameter, is attached at the center using a series of screws. Fabricating the window in two parts proved simpler particularly due to the difficulties in machining pure aluminum. The collimated beam passes entirely through the pure aluminum front window insert and is not attenuated by the rest of the enclosure. The cavity has an internal diameter of 8 cm and a length of 13 cm.

The flange at the rear of the vacuum vessel allows a vacuum pump to be directly attached. A turbomolecular vacuum pump needs to be attached and operates continually to maintain a vacuum during irradiation. An additional pure aluminum back plate, 78 mm in diameter and 1 mm thick, is attached at the end of the vacuum cavity, to shield the vacuum pump attachment from the beam and limit any back scatter, from non-aluminum components.

On either side of the vacuum cavity, figure 3.15, vacuum feed-throughs are placed. The feed-throughs allow the position of the core assembly to be adjusted during
Figure 3.15: The different components of the aluminum vacuum vessel are shown. All labeled dimensions are in inches. The front window is 1.5 ± 0.005 mm thick and 4 cm in diameter. The cavity has an internal diameter of 8 cm and a length of 13 cm. An additional pure aluminum back plate, 78 mm in diameter and 1 mm thick, is attached at the end of the vacuum cavity and omitted for clarity. Feed-throughs facilitate positioning the core within the vessel and provide a path for the thermistor wires outside of the vessel while maintaining a vacuum. Reproduced with the authors permission (Jean Dessureault, email communication, April 2023)
construction in addition to providing a path for the thermistor wires to the outside of the vessel without compromising the vacuum. Both feed-throughs are placed such that they are within the vessel wall and do not protrude into the vacuum cavity to limit any scatter effects.

3.5.2 Thermistor Calibration

An Amphenol© (Wallington, CT) AN6N4 negative thermal coefficient, NTC, thermistor was chosen as the temperature sensor. The cylindrical probe has an outer diameter of 0.48 mm and a length of 1.5 mm. A nickel oxide chip is enclosed within a glass tip, while a polyimide sleeve encapsulates the remainder of the thermistor body. Platinum wires connect the nickel oxide chip to external nickel wires, 0.056 mm diameter. The polyimide sleeve is additionally filled with epoxy resin. An image of the thermistor used is shown in figure 3.16, in addition to a diagram showing the different components.

NTC thermistors show a decrease in resistance as the temperature increases. The temperature can be expressed as a function of thermistor resistance using equation 3.9.

\[
\frac{1}{T} = \frac{1}{\beta} \ln \frac{R}{R_0} + \frac{1}{T_0}
\]  

(3.9)

Where, \( T_0 \) denotes the reference temperature taken to be 298.15 K, \( \beta \) a constant that is a property of the particular thermistor being used is material dependent and varies between identical thermistors, and \( R_0 \) represents the resistance measured at temperature \( T_0 \).

An automated system is used to calibrate the thermistor, and is used to calibrate all thermistors used in NRC calorimetry standards. The system is fully described by
Seuntjens et al [144]. Platinum resistance probes, RTDs, with temperature calibrations traceable to NRC temperature standards are used to determine the temperature of a water bath. Thermistors are placed in the water bath in addition to the RTD probes. The water bath temperature is varied between 15 °C and 30 °C in 0.5 °C steps. At each temperature step the thermistor is allowed sufficient time to reach thermal equilibrium with the bath, on the order of 20 minutes. The RTD probes provide the temperature of the bath and consequently the temperature sensed by the
thermistor, allowing $R_0$ to be directly derived. A simple fit of the data then allows $\beta$ to be determined and the thermistor’s temperature response characterized between 15 °C and 30 °C.

### 3.5.3 Core Assembly

The aluminum core was cut from a 0.5 mm thick pure aluminum foil using a CNC milling machine. The dimensions of the core were measured using a micrometer as $40.190 \pm 0.005 \text{ mm} \times 0.317 \pm 0.005 \text{ mm}$. The thickness of the core was determined by NRC dimensional standards using a coordinate measuring machine to be $0.509 \pm 0.005 \text{ mm}$, traceable to dimensional metrology standards. The thermistor is then fixed in place on the surface of the aluminum core using Pelco® (Fresno, CA) High Performance Nickel Paste. Images captured with an optical microscope, figure 3.17, are used to estimate the contact area between the nickel paste and the aluminum core for the thermal simulations. The masses of all components of the core assembly, including all adhesives, were determined by sequentially weighing the core assembly as additional components were added.

Polyimide aerogel supports are attached to the aluminum core using Locitite Hysol 1 C® (Wesylake, OH) epoxy adhesive. A 3D printed stage, figure 3.18, holds the core in place allowing the adhesive to cure in the desired position. The 3D printed stage was designed to allow the core to be placed at the desired position within the cavity, in alignment with the feed-throughs. Once the adhesive is cured the core is placed within the cavity using the 3D printed stage and the ends of the aerogel supports glued to the feed-throughs using Locitite Hysol 1 C® adhesive. After the final adhesive bond is cured the 3D stage is removed leaving the core suspended in the desired position.

At 0.5 mm thick the core proved to be exceedingly fragile during construction.
Figure 3.17: A optical microscope acquired image of the thermistor affixed to the core using nickel paste, the image is used to estimate the contact area between the thermistor and core. The mass of the nickel paste was measured to be $4.01 \pm 0.05 \times 10^{-3}$ g.

Manipulation of the feed-throughs to position the core resulted in a slight non-linear deformation, which proved difficult to characterize.

Figure 3.18: Left: 3D printed stage with the core and aerogel supports shown prior to being glued. Right: 3D printed stage in position within the vacuum vessel prior to attaching the aerogel supports to the feed-throughs. The 3D printed stage is removed once all adhesives have cured.
3.6 Conclusion

The dose to the aluminum core in air was used as the parameter to assess the performance of the calorimeter. The radiation transport correction for the effect of the vessel, $k_{\text{vessel}}$, was derived using EGSnrc to be between $1.055 \pm 0.005$ and $1.033 \pm 0.005$ depending on beam energy. Additionally, the impact of polarization was assessed using Geant4 and was deemed to be negligible.

Finite element modeling based thermal simulations were used to derive a heat loss correction for the calorimeter design, $k_{ht}$, of $1.030 \pm 0.002$. A preliminary prototype was constructed based on the simulated design with the aim of assessing the feasibility of the approach and validating the simulation results.
Chapter 4

First Tests and Proof of Principle

4.1 Introduction

The calorimeter prototype was used to perform measurements on the BMIT-ID beamline at the CLS. Despite the slight deformation of the core, outlined in the preceding chapter, these measurements are crucial in assessing the feasibility of the design. The small field size, keV energy and high dose rate of the synchrotron beam, mean that a different beam modality cannot be used to adequately characterize operation.

A major step in determining whether a calorimeter design is feasible is assessing the reproducibility of the radiation induced temperature rise. A reproducible temperature measurement would allow an experimental validation of the $k_{ht}$ correction, by comparing the simulated and measured post-irradiation temperature traces. Additionally, the calorimeter and measurement setup would have to survive transport and be quickly setup to take advantage of the limited access to the beam.

This chapter will outline the experimental setup used and how the radiation
induced temperature rise is determined. The second half of the chapter will use the
data to validate $k_{ht}$ and derive a preliminary uncertainty budget for the calculation of
the absorbed dose to the aluminum core in air. The chapter concludes with a number
of adjustments for a second iteration of the design, based on the data collected.

4.2 Methods

Figure 4.1 shows the irradiation setup used to test the feasibility of the calorimeter.
The synchrotron beam is collimated at the entrance of the irradiation room, but an
additional steel cylinder, 25 mm thick with a 36 mm x 2 mm rectangular slit, was
used to provide a more well-defined radiation field.

The calorimeter is aligned such that the core is within the uniform portion of
the field. Alignment was verified by taking an x-ray image during irradiation using
the beamline sCMOS imager system with 6.5 $\mu$m resolution. The synchrotron ring
beam current, which ultimately determines the fluence rate, is run in ‘top-up’ mode
resulting in a constant fluence rate which is continuously reported by the facility
information system and noted before each irradiation set. The calorimeter enclosure
was kept at a pressure of $3 \times 10^{-7}$ mbar to eliminate conductive heat losses to air. The
experimental setup and alignment was performed such that the calorimeter was ready
for measurements within two hours from arrival, including any settling time. Ease of
setup, demonstrated during these measurements, was a design constraint to maximize
the number of irradiations performed during limited beam access.

A wiggler magnetic field strength of 3.7 T was used for all irradiations. The
calorimeter was irradiated for 15 s using the monochromatic x-ray beam by opening
the beamline shutter, with approximately 1 minute between irradiations. A 15 second
irradiation time was chosen to result in a measurable temperature rise at the lowest
dose rates while minimizing the extrapolation uncertainty arising from long irradiation
times. The transit time of the shutter is reported to be 0.018 s. The resistance of
the thermistor was sampled every 400 ms using a calibrated Keysight HP 3458A
multimeter with high stability option (002) and the data plotted in real-time. Direct
readout of the thermistor as opposed to using a bridge circuit was chosen to simplify
the setup and satisfy the portability/robustness requirement of the design.

The fitting and determination of the radiation induced temperature rise was
automated and performed once data acquisition was complete, using a purpose built program. The software principles are described in appendix B. The linear fitting post-irradiation was started 4 seconds after the end of an irradiation to avoid the influence of any heat sharing effects between the different core components. By automating the readout and analysis procedure, the user has no influence on what portions of the temperature trace to use for the extrapolation procedure. Additionally, all irradiation data is used with no runs being removed, in doing so any potential user bias is eliminated. After a fixed number of runs, the calorimeter was allowed to come into thermal equilibrium again before irradiations resumed. The number of runs were chosen such that the calorimeter would return to thermal equilibrium with the environment in a reasonable amount of time, on the order of 20 mins. Radiochromic film was irradiated on the primary collimator surface and used to model the relative fluence distribution of each synchrotron beam used. The reconstructed source models are then used to derive the radiation transport correction $k_{vessel}$.

In an attempt to verify that the calorimeter measured radiation induced temperature rise was consistent with the thermal simulations the thermistor was purposely irradiated by horizontally translating the calorimeter with respect to the primary collimator. The resulting temperature trace was then qualitatively compared to a simulated temperature trace, that included direct thermistor heating, shown in figure 3.11.

### 4.3 Results and Discussion

The preliminary measurements showed adequate signal-to-noise performance. Two temperature traces are shown in figure 4.2. As the dose rate decreases with increasing
Figure 4.2: Calorimeter measured temperature traces of a 15 second irradiation with a 65 keV, left, and 140 keV, right, beam. The higher dose rate 65 keV shows no influence of noise as opposed to the significantly lower dose rate 140 keV beam.

beam energy the influence of noise on the measured signal increases and consequently affects the reproducibilitly of the temperature rise. The mean derived temperature rise for a typical set of 15 irradiations for the 140 keV, lowest dose rate beam, showed an experimental type A standard uncertainty [143] of 0.6 % for a temperature rise of 1.19 mK. The reproducibility of the temperature rise for the remaining higher dose rate beams is less than 0.2 %, table 4.1. The significant reduction in noise for higher dose rates beams, shown in figure 4.2, implies that the reduced temperature reproducibility is due to the influence of noise on the linear fits applied to the temperature trace.

Table 4.1: Reproducibility of synchrotron radiation induced temperature rise

<table>
<thead>
<tr>
<th>E (keV)</th>
<th>Temp Rise (mK)</th>
<th>Std. error of the mean Temp Rise (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>140</td>
<td>1.19</td>
<td>0.6</td>
</tr>
<tr>
<td>115</td>
<td>5.22</td>
<td>0.1</td>
</tr>
<tr>
<td>100</td>
<td>11.03</td>
<td>0.1</td>
</tr>
<tr>
<td>83</td>
<td>33.38</td>
<td>0.1</td>
</tr>
</tbody>
</table>
The calorimeter background temperature drift was observed to be sensitive to room temperature, figure 4.3. This sensitivity, despite the high vacuum within the calorimeter vessel, is consistent with thermal simulations indicating that the thermistor leads are a significant heat-conduction pathway. Further measurements at the NRC with improved thermal insulation of the calorimeter resulted in some improvement in the observed sensitivity to ambient temperature drifts. Analysis showed that the short irradiation time and consequently the use of linear fits to perform an extrapolation...
Figure 4.4: Measured temperature rise as a function of mid-irradiation time for a set of irradiations using the 140 keV beam. The random distribution of the measured temperature rise as a function of mid-irradiation time, implies that the impact of background variations is negligible. This is highlighted by the linear regression line shown.

Over a period equal to half the irradiation time, resulted in a negligible impact of background variations on the reproducibility of the radiation induced temperature rise for the time scale of interest. This can be attributed to the time constant for the change in the background sensed by the core being at least an order of magnitude larger than the irradiation time. Figure 4.4 shows the measured temperature rise of the set of irradiations shown in figure 4.3, as a function of mid-irradiation time. The random distribution of the measured temperature rises as a function of time implies that the impact of background variations is negligible.

As a first validation of the thermal model, both the measured and simulated
temperature traces were normalized with respect to the extrapolated temperature at
the end of each irradiation. By determining the radiation induced temperature rise
for both the simulated and measured traces an estimate of the validity of the model
used and thus the heat loss correction factor uncertainty can be obtained. Simulated
and measured temperature traces showed agreement at the 0.1 % level (in terms of
the normalized radiation-induced temperature rise) and the conduction correction
factor, $k_{ht}$, was determined to be $1.030 \pm 0.002$. It is worth reiterating that while
$k_{ht}$ is approximately 10 times greater than for conventional water calorimeters it is
the same order of magnitude as graphite calorimeters reported in the literature [27].
A large $k_{ht}$ correction was expected given the small thermal mass of the core and
motivated the extensive thermal modeling performed. EGSnrc simulations, showed
that the beam divergence resulted in energy deposition in the Nickel paste surrounding
the thermistor, an effect not modeled within the COMSOL® simulation. Subsequent
simulations indicated that the magnitude of the impact on the conductivity correction
was of the order of 0.2 %. Since it was not possible to model the paste accurately,
an additional uncertainty component was included in the overall uncertainty for $k_{ht}$
given above.

The primary estimate of the uncertainty in the conduction correction is based
on the difference between the normalized radiation induced temperature rise for the
simulated and measured temperature traces, as shown in figure 4.5. This approach was
based on previous investigations at NRC [27] and provides an overall assessment of the
validity of the model. Each irradiation is normalized with respect to the temperature
given by the post-irradiation linear fit when the beam is switched off. The normalized
post-irradiation temperature fit is then extrapolated to the irradiation mid-point,
resulting in the normalized radiation induced temperature rise. The average radiation
Figure 4.5: An illustration of the normalization procedure used to estimate the uncertainty in the conduction correction factor, $k_{ht}$. A plot of the measured and simulated normalized temperature traces, is shown. Extrapolations of the linear fits to the irradiation mid point are shown by the dashed lines. The relative difference at the irradiation mid-point is shown in the insert, used as a conservative estimate of the simulation uncertainty component of $k_{ht}$.

induced temperature rise for all the normalized fits is then calculated. The same normalization and fitting procedure is done for the thermal simulation trace. The relative difference between the average normalized experimental temperature rise and the normalized simulation temperature rise is used as the simulation uncertainty component of $k_{ht}$. This is combined with the component described above related to beam divergence to give the overall uncertainty for this correction.

As an additional verification of the thermal modeling the thermistor was directly irradiated. The resulting temperature trace displayed the same characteristic behavior observed in figure 3.11, with a rapid falloff of the thermistor readout temperature
immediately following irradiation. While this characteristic behavior, due to the heat sharing between the thermistor and core, was qualitatively reproduced any quantitative comparison would be less meaningful given the difficulty in determining the amount of nickel paste being directly irradiated. Nevertheless the ability to reproduce this behavior lends further confidence to the accuracy of the thermal model and our understanding of the calorimeter’s performance.

Based on the current results, an uncertainty budget for the highest energy, and lowest dose rate beam, is presented in table 4.2 based on the components of equation 3.1. The deformation in the core means that the absorbed dose to aluminum in air cannot be explicitly determined, nevertheless an assessment of the overall uncertainty on that determination is possible based on the results obtained. An overall uncertainty of 0.84% was determined for the 140 keV beam for the absorbed dose to the aluminum core in air. The largest contributor to the overall uncertainty was the reproducibility of the temperature rise. The large type A uncertainty on the temperature rise is attributed to the increasing influence of electrical noise for the small temperature rise being measured. As the temperature rise increases the reproducibility of the temperature rise improves, as seen for the lower energy higher dose rate beams in table 4.1.

Measurements performed using the calorimeter prototype prove the feasibility of the approach. Nevertheless a number of issues can be identified to improve a second iteration of the prototype. Improved electrical shielding of the thermistor wires and electrical connections should be explored, to reduce electrical noise and reduce the type A contribution to the uncertainty on the measured temperature rise. The thin core, 0.5 mm, proved to be exceedingly fragile during construction, the resulting deformation in the core being a testament to that. A thicker core should be
Table 4.2: A preliminary uncertainty budget based on equation 3.1 to assess the feasibility of the design for the 140 keV lowest dose rate and highest energy beam measured.

<table>
<thead>
<tr>
<th>Components of Eq. 3.1</th>
<th>Type A (%)</th>
<th>Type B (%)</th>
<th>Combined Unc. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature Rise</td>
<td>0.65</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermistor Calibration</td>
<td>0.05</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( k_{ht} )</td>
<td>0.20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( k_{vessel} )</td>
<td>0.01</td>
<td>0.50</td>
<td></td>
</tr>
<tr>
<td>Aluminum Specific Heat Capacity</td>
<td>0.12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Positioning</td>
<td>0.05</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( D_{core,air} )</td>
<td></td>
<td></td>
<td>0.84 (k=1)</td>
</tr>
</tbody>
</table>

investigated for increased durability and ease of construction even at the expense of greater volume averaging. An increased thermal mass would also decrease the heat loss correction and reduce the impact of any radiation induced thermistor heating due to energy deposition in the thermistor or surrounding nickel paste.

A secondary collimator at the surface of the calorimeter, made of a sufficiently high density material, would allow the beam to be further collimated to reduce beam divergence and further reduce direct energy deposition in both the nickel paste and thermistor. In doing so the \( k_{col} \) component of \( k_{vessel} \) is also reduced, consequently the calorimeter measurement becomes insensitive to the distance between the detector and the primary collimator.

4.4 Conclusion

These preliminary tests have shown the feasibility of the prototype aluminum calorimeter to measure millimeter-sized monochromatic x-ray beams. Performance was assessed
by determining the absorbed dose to the aluminum core for an incident 140 keV monochromatic x-ray beam. The effect of scatter and attenuation due to the vacuum vessel was modeled using the EGSnrc Monte Carlo code, and the results presented in the previous chapter, a correction of $1.033 \pm 0.006$ was derived. Finite element modeling simulations were used to model the temperature response of the calorimeter to the radiation induced temperature rise, and the measurements used to validate the approach. The correction for conductive heat losses was determined to be $1.030 \pm 0.002$. A preliminary uncertainty budget was developed, which indicates that the standard uncertainty in the determination of absorbed dose to the aluminum core in air was 0.84 %. A second iteration of the calorimeter prototype was developed to address some of the concerns identified by these measurements and is the focus of the next chapter.
Chapter 5

Second Prototype and Validation

5.1 Introduction

Based on the results of the proof-of-principle study, a new calorimeter was constructed. A number of modifications to the original design, mainly a larger core, were implemented to improve the performance of the calorimeter. A series of calorimeter measurements were performed for monochromatic x-ray beams in the 83 - 140 keV range to determine the absorbed dose to the aluminum core in air. Short-term reproducibility of the calorimeter readings can be assessed by comparing measurements of the same beam using both calorimeter prototypes. Short-term reproducibility would serve to demonstrate the precision of the construction methods used, the accuracy of the thermistor calibrations and lend confidence to the accuracy of the simulations used. Experiments were performed over a period of two years using the first prototype allowing the long-term reproducibility and robustness of the design to be evaluated as well.

The new calorimeter prototype is expected to be fully characterized by both the
radiation transport and heat loss simulations. It is then important to provide an independent validation of the calorimeter measurements. This would typically be performed either by comparison to a detector of known response in the synchrotron beam being measured or by performing measurements in another well characterized beam. The calorimeter design is uniquely suited to the measurement of high dose rate millimeter sized x-ray beams, which are not readily available. The use of other sources such as larger field size and high dose rate MeV energy photon sources would introduce additional corrections and make the comparison less meaningful. Increased scatter from the side walls being a particular concern, due to the resulting increase in sensitivity of $k_{vessel}$ to the properties of the incident beam. Consequently, an independent validation using a different source was not pursued. The absence of well characterized detectors for use in synchrotron produced monochromatic x-ray beams was the main motivator for this work. Nevertheless, an air-kerma based validation was attempted using a diamond detector with a calibration, using a kV x-ray tube, traceable to a FAC primary standard. By determining the air-kerma rate for each of the monochromatic beams used in the 83 - 140 keV range using a microDiamond detector, and comparing to measurements of air-kerma based on the calorimeter results the calorimeter approach will be partially validated.

This chapter will outline the modifications to the original calorimeter design. Recalculated correction factors, taking into account the design modifications are presented. The experimental setup used to determine the absorbed dose to the aluminum core is described and an uncertainty budget derived for the calculation of $D_{core,air}$. The chapter concludes by outlining a series of air-kerma measurements using a diamond detector, and the methodology to convert $D_{core,air}$ to air-kerma. The air-kerma results will then be used to confirm the calorimeter based measurements.
5.2 Design Modifications

The measurements performed with the first calorimeter prototype outlined some weaknesses in the design. In an attempt to reduce the electrical noise observed, electrically conductive silver paste was applied to the electrical connections between the thermistor wires and the readout cables. The addition of conductive paste will improve the electrical connection and potentially reduce the noise observed.

Deformation of the calorimeter core was identified as a major concern in the operation of the calorimeter. Consequently, the vertical dimension of the core was increased to 1 mm, while maintaining the same dimensions of all adhesives, aerogel supports and nickel paste used. The increased core mass is expected to reduce the $k_{ht}$ correction significantly. Mass fractions of the new calorimeter core and surrounding components are shown in table 5.1. By maintaining the same masses for all non-core components, the sensitivity of the core temperature to direct energy deposition in the thermistor and nickel paste is reduced. The thermal simulations were repeated with the new core dimensions and a $k_{ht}$ correction of $1.0129 \pm 0.005$ is derived, less than half the correction for the original prototype. An extensive sensitivity study showed that despite the good agreement with simulation, the need to determine the contact area between the nickel paste and the aluminum core is a significant contributor to the overall simulation result.

A sensitivity analysis was performed by varying the contact area between the nickel paste and aluminum core. Doubling the measured contact area resulted in a 0.6 % change which is added to the initial uncertainty estimate of 0.2 %. A conservative rectangular distribution is assumed to model the results of the sensitivity study, such that $u_{(k_{ht})}(k = 1) = U_{(k_{ht})}/\sqrt{3} = 0.8/\sqrt{3}$. Based on the results of the sensitivity analysis the overall uncertainty on the conduction correction is expanded from 0.2 %
Table 5.1: Mass fractions of core components for the second calorimeter prototype.

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass ±5 (\cdot) 10(^{-5}) (g)</th>
<th>Mass Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum Core</td>
<td>0.35010</td>
<td>0.944</td>
</tr>
<tr>
<td>Thermistor</td>
<td>0.00022</td>
<td>0.001</td>
</tr>
<tr>
<td>Wire</td>
<td>0.00419</td>
<td>0.011</td>
</tr>
<tr>
<td>Nickel Paste</td>
<td>0.00514</td>
<td>0.014</td>
</tr>
<tr>
<td>Aerogel</td>
<td>0.01104</td>
<td>0.030</td>
</tr>
</tbody>
</table>

Beam divergence was identified as the cause of energy deposition in the nickel paste surrounding the thermistor, in addition to increasing the sensitivity to changes in the distance between the collimator and core. To reduce this effect a secondary collimator was constructed from a tungsten alloy, commonly called hevimet. Hvimet, HD18 (Mi-Tech metals, Indianapolis, IN), was chosen for its high density (90 % Tungsten, 6 % Nickel, 4 % Copper) and machinability allowing the secondary collimator to be only 1 mm thick. The thin secondary collimator would then allow the beam to be further collimated while minimizing collimator scatter. Figure 5.1 shows the collimator fixed to the calorimeter front window with a 36 mm x 2 mm slot matching the primary collimator opening. Recalculated \(k_{\text{vessel}}\) corrections modeling the secondary collimator are shown in table 5.2. Note the reduction in the \(k_{\text{col}}\) component of \(k_{\text{vessel}}\) indicating the increased collimation of the beam relative to the earlier design. Increased collimation results in negligible energy deposition in the nickel paste as well, implying that the 0.5 % uncertainty assigned to \(k_{\text{hi}}\) is likely an overly conservative estimate.

The reduction in \(k_{\text{col}}\) results in a larger overall \(k_{\text{vessel}}\) correction due to the fortuitous cancellation of correction factors for the first prototype. Nevertheless the reduced
sensitivity to the divergence of the beam and consequently the sensitivity to the core
to primary collimator distance, improves the confidence in the calculated $k_{vessel}$ values.

Reducing the thickness of the vacuum vessel to avoid obstructing the field of view
of the CLS sCMOS camera, used to position the calorimeter, was investigated. Due
to operational constraints of the manufacturing process used to construct the vacuum
vessel, and the long fabrication times quoted, modifications to the vessel were avoided.
It is nevertheless believed that the positioning of the calorimeter can still be achieved
with sufficient accuracy although it would be simplified with the ability to visualize

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure5.1.png}
\caption{An image of the second calorimeter prototype showing the secondary
collimator fixed to the calorimeter front window. The secondary collimator is co-axial
with the primary collimator with an identical opening of 36 mm x 2 mm and a thickness
of 1 mm. The collimator is comprised of Hevimet alloy, (90 % Tungsten, 6 % Nickel,
4 % Copper).}
\end{figure}
Table 5.2: EGSnrc calculated $k_{vessel}$ corrections and components for the second prototype calorimeter.

<table>
<thead>
<tr>
<th>E (keV)</th>
<th>$k_{attn}$</th>
<th>$k_{scatter}$</th>
<th>$k_{col}$</th>
<th>$k_{vessel}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>140</td>
<td>1.057</td>
<td>1.000</td>
<td>0.998</td>
<td>1.054</td>
</tr>
<tr>
<td>115</td>
<td>1.063</td>
<td>1.000</td>
<td>0.998</td>
<td>1.061</td>
</tr>
<tr>
<td>100</td>
<td>1.069</td>
<td>1.000</td>
<td>0.998</td>
<td>1.066</td>
</tr>
<tr>
<td>83</td>
<td>1.081</td>
<td>1.000</td>
<td>0.997</td>
<td>1.078</td>
</tr>
</tbody>
</table>

The entire core using the beamline camera. The values of $k_{ht}$ and $k_{vessel}$ derived in this section will be used throughout this chapter to assess the feasibility and attempt to validate the second calorimeter prototype.

5.3 Methods

5.3.1 Irradiation Setup

Figure 5.2 shows the irradiation setup used, in addition to the relevant distances along the beamline. The irradiation setup is similar to that used to determine the feasibility of the first prototype. Initially the collimator was machined from a steel disc, this was in part due to time constraints. In this setup the circular collimator has been replaced with a rectangular one, due to the unnecessary extra degree of freedom provided by the circular collimator. The rectangular collimator has an identical opening, is 25.4 mm thick and is meant to simplify the setup procedure. A wiggler magnetic field strength of 3.7 T was once again used for all irradiations. A notable difference is the presence of a PTW microDiamond (PTW 60019, Freiburg, Germany) detector. The detector is placed edge on, figure 2.6, such that the smallest dimension of the sensitive diamond element, 1 $\mu$m, is along the vertical direction while the 3 mm diamond disc...
diameter is parallel to the beam. Current and charge readout from the diamond detector was achieved using an electrometer (PTW Unidose Webline 10023, Freiburg, Germany) applying no voltage across the detector. The diamond detector serves two purposes, by being on a two dimensional stage it can be used to provide real-time estimates of the synchrotron beam profile and by placing the diamond in the beam center, measurements can be used to validate the calorimeter readings.

The calorimeter is aligned such that the core is within the uniform portion of the field. Alignment was once again verified by taking an x-ray image during irradiation using the beamline sCMOS imager system and achieved within ± 13 µm. The microDiamond is then used to verify that an acceptable beam profile is achieved, by scanning the field in both the horizontal and vertical direction. A charge measurement is then performed at the center of the beam, co-axial with the center of the calorimeter core, before the diamond is moved well outside the collimated synchrotron beam as to not interfere with the calorimeter measurements. The synchrotron ring beam current, which ultimately determines the fluence rate, is run in ‘top-up’ mode resulting in a constant fluence rate which is continuously reported by the facility information system and noted, in addition to the diamond charge reading collected at the beam center before each irradiation set.

The calorimeter enclosure was kept at a pressure of 3 x 10^{-7} mbar to eliminate conductive heat losses to air. Calorimeter irradiations were performed for 15 s using the monochromatic x-ray beams by opening the beamline shutter, with approximately 1 minute between irradiations. A 15 second irradiation time was once again chosen to be consistent with our earlier measurements with the first prototype. The transit time of the shutter is reported to be 0.018 s. The resistance of the thermistor was sampled every 400 ms using a calibrated Keysight HP 3458A multimeter with high
stability option (002) and the data plotted in real-time.

The fitting and determination of the radiation induced temperature rise was performed using the same purpose built program with the updated corrections described in the preceding section. The linear fitting post-irradiation was started 4 seconds after the end of an irradiation to avoid the influence of any heat sharing effects between the different core components. Once more, all irradiation data is used with no runs being removed. After a fixed number of runs, the calorimeter was allowed to come into thermal equilibrium again before irradiations resumed. Radiochromic film was

![Image of irradiation setup](image)

*Figure 5.2:* The top image shows the irradiation setup used. The beam is incident from the left onto the collimator shown. The microDiamond can be seen in the center of the beam on a two axis stage. Prior to calorimeter measurements the microDiamond is translated such that it is well outside the beam. The calorimeter is visible on the right side of the image, note the CLS sCMOS camera is omitted for clarity. A diagram of the setup is also shown in the bottom image with the associated relative positions, note the 56.32 m refers to the distance from the photon source at the beginning of the beamline.
irradiated on the primary collimator surface and used to model the relative fluence distribution of each synchrotron beam used. The reconstructed source models are then used to derive the radiation transport correction $k_{\text{vessel}}$.

### 5.3.2 Diamond Detector Based Validation

Ideally a detector other than the calorimeter would be used to determine the absorbed dose to water at the reference depth and used to compare with the calorimeter derived result. The absence of such a detector was the main motivator for this project. A determination of the air-kerma provides a route to independently validate the calorimeter. Air-kerma, $K_{\text{air}}$, is defined as the energy imparted by uncharged particles to charged particles in air, equation 5.1.

$$K_{\text{air}} = \phi(E) \cdot E \cdot (\frac{\mu_{tr}}{\rho})_{\text{air}}(E)$$

(5.1)

The micro-diamond detector used as a beam monitor provided both a stable charge reading and showed an insensitivity to the highest dose rates used in this work. Consequently, the diamond charge measurements recorded at the center of the beam will be used to provide an estimate of the air-kerma along the central axis corresponding to the center of the calorimeter core.

To derive an air-Kerma estimate from the diamond charge readings a calibration is necessary:

$$N_K(E) = \frac{K_{\text{air,MEES}}(E)}{M_{\text{Diamond}}}[\text{mGy/nC}]$$

(5.2)

Where, $N_k(E)$ denotes the air-kerma calibration factor as a function of energy, $M_{\text{Diamond}}$ the diamond charge reading and $K_{\text{air,MEES}}(E)$ the air-kerma rate measured
by the NRC medium energy free-air chamber primary standard at the position of the diamond’s center.

The calorimeter derived absorbed dose, $D_{\text{core,air}}$, must be converted to the air-kerma at the beam center. Since both the air and the aluminum core are subject to the same energy fluence, in the absence of the vacuum vessel, then the air-kerma can be estimated from a ratio of aluminum to air mass energy transfer coefficients. The radiative yield, $g$, has a maximum value of 0.2 % at an energy of 140 keV justifying equating dose to kerma. To determine the air-kerma at the center of the beam, the

![Graph showing mass energy transfer coefficient values as a function of beam energy](image)

**Figure 5.3:** Diamond mass energy transfer coefficient values calculated as a function of beam energy using the EGSnrc $g$ application.
variation in the beam’s dose rate over the core needs to be considered. A volume averaging correction can be derived based on integrating the film measured beam profile over the surface of the calorimeter perpendicular to the beam. A measurement of the air-kerma can then be derived as:

\[ K_{\text{air}}(E) = D_{\text{Al core, in air}} \cdot \left[ \frac{\mu_{\text{tr}}}{\rho} \right]_{\text{Air}}^{\text{Aluminum}} \cdot k_{\text{vol}} \quad (5.3) \]

Both the diamond and calorimeter then provide independent determinations of the air-kerma along the beam central axis and a comparison allows a validation of both the calorimeter measurements and the Monte Carlo based determination of the absorbed dose to the aluminum core. The microDiamond derived air-kerma rate can be expressed as: \( K_{\text{air,CLS}}(E) = N_K(E) \times M_{\text{Diamond}} \), where \( K_{\text{air,CLS}}(E) \) denotes the synchrotron air-kerma rate as a function of energy. This can be compared to the calorimeter derived air-kerma rate for the same beam, equation 5.3. Preliminary validation of the calorimeter would then be achieved if the air-kerma rates for the same beam derived using the microDiamond and calorimeter agree within uncertainties.

### 5.4 Results and Discussion

#### 5.4.1 Calorimeter Measurements

Measurements using the new calorimeter prototype showed improved reproducibility of the radiation induced temperature rise, particularly for the 140 keV lowest dose rate beam. Table 5.3, shows the induced temperature rise as a function of energy. The largest contributor to the uncertainty in the absorbed dose in the first prototype was due to the reproducibility of the temperature rise at the lowest dose rates, a
0.6 % contribution. The improvement in reproducibility reduces this uncertainty contribution to 0.2 %.

Greater temperature reproducibility can be attributed to improving the electrical connections between the thermistor wires and the resistance measuring digital multi-meter by limiting strains on the wire and the careful application of electrically conductive adhesive. Additionally, the use of the diamond detector current measurements to monitor the stability of the monochromator ensured that there was no variation in the monochromator output prior to an irradiation set. Measurements using the first calorimeter prototype did not consider the stability of the monochromator and could have potentially been influenced by output variations due to thermal instabilities. Monochromator variations typically occur if the synchrotron source experiences a fault resulting in no beam or when the beam energy is changed. Large energy changes, resulting in large changes in dose rate and consequently a change in the thermal load on the monochromator, require some time (on the order of 15 - 30 minutes) for the monochromator to become stable.

The result in figure 4.5 was reproduced using thermal simulations of the new calorimeter design. Table 5.4, shows the proposed uncertainty budget for the determin-

**Table 5.3:** Reproducibility of radiation induced temperature rise using the second prototype as a function of beam energy.

<table>
<thead>
<tr>
<th>E (keV)</th>
<th>ΔT (mK)</th>
<th>Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>83</td>
<td>28.174</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>100</td>
<td>11.726</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>115</td>
<td>5.190</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>140</td>
<td>1.114</td>
<td>0.2</td>
</tr>
</tbody>
</table>
nation of $D_{\text{core,air}}$ using the new prototype. An overall uncertainty for the determination of $D_{\text{core,air}}$ of 0.75% is estimated. While this is a marginal improvement, the estimate is more rigorous, and when compared to the first prototype it should also be noted that the design nevertheless still has many advantages. A rigid core with increased resistance to deformation is crucial, whilst the use of a second collimator decreased the impact of heat sharing effects and increased the confidence in the determination of the field size. In an attempt to gain some insight into the reproducibility of the construction methods used, measurements were performed using the first prototype. $D_{\text{core,air}}$ values were compared for measurements of the same beam, and agreement was achieved at the 1.5% level. Agreement within uncertainties, despite the deformed core of the first prototype, implies that the manufacturing process is consistent between both prototypes. Additionally, both prototypes have survived several trips to the beamline by being hand carried through airport security, which serves as a testament to the robustness of the design. The consistent performance of the first prototype over a period of 3 years lends evidence to the long term reproducibility of the measurements.

5.4.2 Air-kerma Based Validation

Attempts to calibrate the diamond using a number of different filter and kV combinations were performed at NRC, where the air-kerma was determined for each kV and filter combination using the MEES free-air chamber standard. Finding a beam with a sufficiently high dose rate to ensure both the pre-irradiation of the diamond and a stable charge reading proved difficult. A relatively broad beam with a tube potential of 200 kV and 3.0802 mm of copper filtration was found to provide adequate stability, at the 0.3% level. The resulting beam has an effective energy of 120 keV and half-value layer of 2.451 mm of copper. An $N_K$ of 806 ± 3 mGy/nC is determined.
Table 5.4: A preliminary uncertainty budget based on equation 3.1 to assess the feasibility of the design modifications for the 140 keV lowest dose rate and highest energy beam measured.

<table>
<thead>
<tr>
<th>Components of Eq.3.1</th>
<th>Type A (%)</th>
<th>Type B (%)</th>
<th>Combined Unc. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature Rise</td>
<td>0.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermistor Calibration</td>
<td>0.05</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$k_{ht}$</td>
<td>0.50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$k_{vessel}$</td>
<td>0.01</td>
<td>0.50</td>
<td></td>
</tr>
<tr>
<td>Aluminum Specific Heat Capacity</td>
<td>0.12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Positioning</td>
<td>0.05</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$D_{core,air}$</td>
<td></td>
<td>0.75 (k=1)</td>
<td></td>
</tr>
</tbody>
</table>

using equation 5.2.

The variation in $N_K$ as a function of beam energy would be due to the differences in scatter contributions and the variation in the mass energy transfer coefficient of diamond as a function of energy, figure 5.3. For the relatively large calibration field size, 10 cm × 10 cm, scatter off the diamond chamber stem is a concern. Due to the small synchrotron beam size, the stem effect is expected to be reduced resulting in a change in the diamond response. The variation in mass energy transfer coefficient is assumed to be the largest contributor to the change in the diamond response as a function of beam energy. By determining the ratio of mass energy transfer coefficients, using the EGSnrc g application, the $N_K$ calibration at 120 keV effective energy can be corrected for each energy and an estimate for the air-kerma determined at a monochromatic beam of energy $E$ as:

$$N_K(E) = N_K(120 \text{ keV}) \cdot \left[\frac{\mu_{tr,diamond}}{\rho_{diamond}}\right]_{120\text{keV}}^E$$

(5.4)
Table 5.5: MicroDiamond air-kerma rate measurements based on charge collected when the diamond detector is positioned at the center of the field defined by the collimator.

<table>
<thead>
<tr>
<th>E (keV)</th>
<th>M (nC/min)</th>
<th>N_K (mGy/nC)</th>
<th>K_air (mGy/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>83</td>
<td>65.0</td>
<td>895</td>
<td>970 ± 19</td>
</tr>
<tr>
<td>100</td>
<td>38.0</td>
<td>855</td>
<td>541 ± 11</td>
</tr>
<tr>
<td>115</td>
<td>20.2</td>
<td>818</td>
<td>275 ± 6</td>
</tr>
<tr>
<td>140</td>
<td>5.5</td>
<td>766</td>
<td>70 ± 1</td>
</tr>
</tbody>
</table>

The linear variation in mass-energy transfer coefficients over the energy range in figure 5.3, also serves to justify using the effective energy of the broad spectrum calibration beam as the beam quality specifier. The air-kerma calibration factor determined using equation 5.4 for a 118 keV beam was compared to the air-kerma calibration factor derived through measurement of a narrow beam spectrum with an effective energy of 118 keV, equation 5.2.

The 118 keV beam resulted in substantial drift in the diamond charge reading due to its low dose rate. A comparison between both N_K values showed a 2 % difference and is used as an estimate of the uncertainty on the N_K values derived using equation 5.4. This relatively large uncertainty is a reflection of both the large drift observed and the different contributions of scattering off the chamber stem between both beams, which was not considered. Diamond charge measurements performed at the light source were found to be reproducible at the 0.3 % level and consequently an overall uncertainty for the diamond based air-kerma determination, by multiplying the diamond charge reading by N_K, of 2.0 % is derived. Table 5.5 shows the diamond based air-kerma rates for the monochromatic beams measured at the CLS.
Calorimeter measured air-kerma rates are derived using equation 5.3. $k_{vol}$ corrections were on the order of 2.2% for all the beams measured. A $k_{vol}$ uncertainty contribution of 0.2% is assumed and is meant to incorporate the uncertainty in positioning the diamond detector in the beam center as well. Whilst the ratio of mass energy transfer coefficients is known with an uncertainty of less than 0.3% in this energy range [142], an expanded uncertainty of 0.5% is used, to account for the size of the core in the beam direction. An overall uncertainty on the calorimeter derived air-kerma rate of 0.95% is assumed.

A plot of the ratio of microDiamond determined air-kerma rates and the corresponding calorimeter determined air-kerma rates is shown in figure 5.4. All air-kerma rate values agree within the associated uncertainties at $k=1$. Air-kerma measurements with the microDiamond are based on charge measurements in a calibrated detector and as such derive the air-kerma rate in an entirely different way to the calorimeter. The calorimeter air-kerma determination is based on the derivation of $D_{\text{core,air}}$, which is the first step in determining the absorbed dose to water. The agreement for all energies serves as an independent validation of the calorimeter prototype in particular the methods used to model the energy deposition in the core, the thermal model used and the measurement of the temperature rise.
Figure 5.4: Ratio of calorimeter and diamond measured air-kerma rates as a function of synchrotron beam energy. The dotted red lines show bounds for agreement at the 1.5 % level, well within uncertainties.
5.5 Conclusion

These measurements provide evidence of the successful operation of the new prototype. Additionally, agreement within uncertainties with the first prototype confirms the reproducibility, robustness of the design and the validity of the uncertainty estimates used for $D_{\text{core,air}}$. An uncertainty of 0.75% is derived for $D_{\text{core,air}}$. While a marginal improvement on the first design, the modifications are justified due to the increased resistance to core deformation and greater confidence in the determination of the beam area provided by the new prototype, by reducing the influence of beam divergence.

Independently derived air-kerma rate measurements using both the calorimeter and microDiamond showed agreement at the $< 1.5\%$ level well within uncertainties. This agreement serves to validate the uncertainty estimates used and the procedure to derive $D_{\text{core,air}}$. Determining the absorbed dose to the aluminum core in air is a first step in determining the absorbed dose to water at a depth of 2 cm, the ultimate goal of this work. A thorough validation of the calorimeter would ideally involve comparison with a free air chamber standard based air-kerma rate determination in a synchrotron beam, and will be pursued in the future.
Chapter 6

The Absorbed Dose to Water

6.1 Introduction

In the preceding chapters the operation of the calorimeter along with the radiation transport and thermal modeling were verified. The end goal of this work is the determination of the absorbed dose to water due to synchrotron produced monochromatic x-ray beams in the 80-140 keV range, at a reference depth of 2 cm in water. A depth of 2 cm is chosen to be consistent with the TG-61 protocol [17], and to ensure adequate build up of secondary charged particles whilst ensuring the primary beam has not been overly attenuated.

The agreement in the derived air-kerma rates using the second calorimeter prototype with an independently calibrated diamond detector at the < 1.5 % level, within measurement uncertainties, lends confidence that the experimental setup can be adequately modeled using EGSnrc. In this chapter a Monte Carlo based conversion will be derived to convert the measured radiation induced temperature rise to the absorbed dose at the desired depth. This process is not unlike the determination of
the air-kerma rate in chapter 5 using the calorimeter, with the only difference being the modeling of the attenuation and scatter of the monochromatic beams in pure water as opposed to air. In addition, the energy deposited by secondary electrons as they traverse the phantom is modeled, a trivial extension of the previous simulations in this energy range.

Two quantities; the central axis dose at a depth of 2 cm in water and the dose area product at the same depth will be calculated. Simulations used will be presented and a resulting Monte Carlo based conversion derived, replacing $k_{vessel}$ in equation 3.1. The merits of each quantity will also be discussed.

Measurements performed with the microDiamond showed that the detector provided a stable response over the range of dose rates used in this work. Additionally, the small detector size, relative ease of alignment and similarity to a farmer type ion chamber, commonly used by medical physicists, make it an ideal detector to calibrate for routine use at the CLS.

An absorbed dose to water calibration factor for the microDiamond will also be derived, for predefined reference conditions, to determine the central axis dose at a depth of 2 cm in water for routine use at the CLS.

### 6.2 Determining Dose to a Point

Absorbed dose to water at a point along the central axis at a depth of 2 cm in a water phantom, $D_{w,2cm}$, is derived using a series of EGSnrc simulations starting from the calorimeter measured radiation induced temperature rise. The geometry used for each simulation, labeled from A to F, is shown in figure 6.1. The multitude of simulations used is strictly not necessary and only two simulations can be used to
derive the necessary correction factor, A and D. However, the simulations allow the components of the Monte Carlo based correction to be independently assessed, similar to the earlier discussion of the contributions to the $k_{\text{vessel}}$ correction.

$D_{w, \, 2\text{cm}}$ can be expressed using equation 6.1, where $k_w$ denotes the Monte Carlo based conversion factor to convert from the absorbed dose to the aluminum core in the vacuum vessel to $D_{w, \, 2\text{cm}}$. Where, $D_{w, \, 2\text{cm}}$ is at the same distance from the primary collimator as the center of the calorimeter core.

$$D_{w, \, 2\text{cm}} = c_{Al} \Delta T k_{ht} k_w$$  \hspace{1cm} (6.1)

$k_w$ can be expressed as a product of the simulations shown in figure 6.1 as:

$$k_w = k_{B,A} k_{C,B} k_{D,C} = k_{D,A}$$  \hspace{1cm} (6.2)

Where, $k_{i,j}$ is meant to represent the ratio of the dose scored in simulation $i$ to that scored by simulation $j$. All simulations are based on the reconstructed synchrotron source profiles, used in the determination of the $k_{\text{vessel}}$ correction. The simulation results, as a function of incident beam energy, are shown in table 6.1.

### Table 6.1: Components of $k_w$ based on the simulations in figure 6.1.

<table>
<thead>
<tr>
<th>E (keV)</th>
<th>$k_{B,A}$</th>
<th>$k_{C,B}$</th>
<th>$k_{D,C}$</th>
<th>$k_w$</th>
</tr>
</thead>
<tbody>
<tr>
<td>83</td>
<td>0.840</td>
<td>0.504</td>
<td>1.136</td>
<td>0.480</td>
</tr>
<tr>
<td>100</td>
<td>0.841</td>
<td>0.671</td>
<td>1.140</td>
<td>0.644</td>
</tr>
<tr>
<td>115</td>
<td>0.842</td>
<td>0.798</td>
<td>1.135</td>
<td>0.763</td>
</tr>
<tr>
<td>140</td>
<td>0.845</td>
<td>0.944</td>
<td>1.144</td>
<td>0.912</td>
</tr>
</tbody>
</table>
Figure 6.1: EGSnrc simulations to derive $k_w$ for both the central axis absorbed dose at a depth of 2 cm and the dose area product at the same depth. Each illustration shows the material composition and dimensions of the scoring volume used. Blue denotes the water phantom. $k_{(i,j)}$ is meant to represent the ratio of the dose scored in simulation $i$ to that scored by simulation $j$. 

$$k_{(i,j)} = \frac{D_i}{D_j}$$
$k_{B,A}$ converts the absorbed dose to the aluminum core in the vacuum vessel to the absorbed dose to the same core in a water phantom, with the core center at a depth of 2 cm. The correction is on the order of 0.84 and can be attributed to the difference in attenuation and scatter between the vessel and phantom. Although it is not trivial to separate the scatter and attenuation contributions to $k_{B,A}$ using EGSnrc, the scatter contributions is expected to be significantly larger than in the low scatter geometry used to calculate $k_{vessel}$.

Our earlier Geant4 based investigation into the influence of polarization on the derived $k_{vessel}$ correction determined that polarization was negligible due to the low scatter geometries simulated.

Although the presence of the phantom introduces additional scatter contributions at depth, the phantom is uniformly composed of liquid water. Any preferential scattering as a function of azimuthal angle, relative to the beam direction, equation 3.5, should not result in changes to the calculated ratio of scored doses due to the symmetry of the phantom. To verify this assumption simulations were repeated using GEANT4 using G4EmLivermorePolarizedPhysics cross-sections to model photon polarization. Simulations were performed with polarization switched on and off and confirmed that the influence of the polarization on the calculated corrections was negligible, justifying the use of EGSnrc.

$k_{C,B}$ constitutes the largest component of $k_w$ and accounts for the material conversion from aluminum to water. This is achieved by simulating identical cores in the phantom and changing the core material from aluminum to water. While large, it should be noted that the material conversion is known with a lower uncertainty, essentially being the ratio of mass energy absorption coefficients of water and aluminum at each beam energy. The uncertainty on the ratio of mass energy absorption
Table 6.2: Monte Carlo calculated aluminum to water material conversion correction compared to the ratio of mass energy absorption coefficients at each energy simulated.

<table>
<thead>
<tr>
<th>E (keV)</th>
<th>(\frac{\mu_{en}}{\rho})_{Al}</th>
<th>(k_{C,B})</th>
<th>(\frac{\mu_{en}}{\rho})_{Water}</th>
<th>(k_{C,B})</th>
</tr>
</thead>
<tbody>
<tr>
<td>83</td>
<td>0.501</td>
<td>0.504</td>
<td>1.007</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>0.668</td>
<td>0.671</td>
<td>1.004</td>
<td></td>
</tr>
<tr>
<td>115</td>
<td>0.793</td>
<td>0.798</td>
<td>1.006</td>
<td></td>
</tr>
<tr>
<td>140</td>
<td>0.934</td>
<td>0.944</td>
<td>1.007</td>
<td></td>
</tr>
</tbody>
</table>

coefficients in this energy range for low Z materials is on the order of 0.2 %, well below the Type B uncertainty assigned to \(k_w\) [145]. Table 6.2 compares \(k_{C,B}\) to the ratio of mass energy absorption coefficients at each energy. It should be noted that the less than 1 % deviation from unity for all energy is due to volume averaging in the beam direction over the core, simulated in \(k_{C,B}\).

The Monte Carlo corrections described so far are independent of the fluence distribution of the source used in the simulation. The dependence on the fluence distribution appears in \(k_{D,C}\) where the dose to a core, comprised of water, in phantom is compared to the dose to a small volume of water, \(1.25 \times 10^{-4}\) cm, at the measurement position. The correction is on the order of 1.14 and in essence accounts for volume averaging over the core. Of the 1.14 correction 1.11 is due to the regions of the core not directly irradiated by the beam, 10 % of the core mass, resulting in an increase in the dose scored once the horizontal dimension of the scoring volume is smaller than the collimated beam, 3.6 cm.

An overall \(k_w\) correction of between 0.480 and 0.912 is derived depending on the beam energy. If the contribution of the material conversion correction \(k_{C,B}\) is decoupled
from $k_w$ such that only the Monte Carlo transport based correction is considered, the correction ranges between 0.959 and 0.973 due to a fortuitous cancellation of the remaining corrections. The particle transport component of the simulation uncertainty would only contribute to the 0.959 - 0.973 component of $k_w$ and not the material conversion. A $k_w$ uncertainty of 0.7% is assumed, this uncertainty is greater than the $k_{vessel}$ uncertainty due to the contribution of volume averaging to the determination of $D_{w, 2cm}$, which is dependent on the modeling of the fluence distribution, a 2.2% effect. The impact of volume averaging on $D_{w, 2cm}$ was determined by modeling several different measured fluence distributions for multiple energies and comparing to the effect of a rectangular distribution, with 2.2% denoting a conservative worse case estimate. An uncertainty budget for the determination of $D_{w, 2cm}$ is presented in table 6.3. Where $k_w$ has been further broken down into the product of volume averaging $k_\phi$, material conversion $k_{mat}$ and Monte Carlo transport $k_{MC}$. The overall uncertainty is dominated by the conservative uncertainty estimates for the $k_{ht}$ and $k_w$ correction factors.

The previously established agreement within uncertainties of air-kerma derived values using the calorimeter with independent microDiamond measurements indicates that the Monte Carlo simulations accurately model both the detector and the synchrotron beam. Nevertheless for completeness a dose to water comparison based on an application of the TG-61 protocol [17] was performed. A Monte Carlo based depth dose correction can be used to convert the calorimeter determined $D_{w, 2cm}$ to the dose at the surface of a water phantom, $D_{w, 0cm}$. With knowledge of the microDiamond determined air-kerma rate from section 5.4.2 an application of the TG-61 protocol can be used to determine $D_{w, 0cm}$ independently as well.

To convert the microDiamond derived air-kerma rate to $D_{w, 0cm}$ the result was
Table 6.3: An uncertainty budget based on equation 6.1 for the determination of $D_{w, 2cm}$ using the second prototype. Where $k_w$ has been further broken down into the product of volume averaging $k_\phi$, material conversion $k_{mat}$ and Monte Carlo transport $k_{MC}$.

<table>
<thead>
<tr>
<th>Components of Eq.6.1</th>
<th>Type A (%)</th>
<th>Type B (%)</th>
<th>Combined Unc. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature Rise</td>
<td>0.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermistor Calibration</td>
<td>0.05</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$k_{ht}$</td>
<td>0.50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$k_{MC}$</td>
<td>0.01</td>
<td>0.50</td>
<td></td>
</tr>
<tr>
<td>$k_{mat}$</td>
<td>0.30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$k_\phi$</td>
<td>0.30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aluminum Specific Heat Capacity</td>
<td>0.12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Positioning</td>
<td>0.05</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$D_{w, 2cm}$ 0.89 (k=1)

multiplied by a back-scatter factor to account for the effect of the phantom on the energy deposited in the microDiamond, values defined in TG-61 were used [17]. The microDiamond stem correction was assumed to be unity and the ratio of mass energy absorption coefficients of water and air calculated in a similar fashion to section 5.4.2. The result was compared to the calorimeter $D_{w, 0cm}$ determined values and agreement was achieved at < 5 % for all energies considered, table 6.4.

Table 6.4: TG-61 based comparison of $D_{w, 0cm}$ estimates using the calorimeter and microDiamond.

<table>
<thead>
<tr>
<th>E (keV)</th>
<th>$K_{air}$ (mGy/s)</th>
<th>$\frac{\mu_{en}}{\rho}<em>{water} \frac{\mu</em>{en}}{\rho}_{air}$</th>
<th>Back-scatter correction</th>
<th>MicroDiamond $D_{w, 0cm}$ (mGy/s)</th>
<th>Calorimeter $D_{w, 0cm}$ (mGy/s)</th>
<th>Depth-dose correction</th>
<th>Calorimeter $D_{w, 2cm}$ (mGy/s)</th>
<th>Agreement</th>
</tr>
</thead>
<tbody>
<tr>
<td>83</td>
<td>969.51</td>
<td>1.079</td>
<td>1.039</td>
<td>1087.15</td>
<td>826.7</td>
<td>1.36</td>
<td>1123.7</td>
<td>3.3 %</td>
</tr>
<tr>
<td>140</td>
<td>69.97</td>
<td>1.106</td>
<td>1.021</td>
<td>78.98</td>
<td>63.6</td>
<td>1.30</td>
<td>82.7</td>
<td>4.6 %</td>
</tr>
</tbody>
</table>

138
The limitations of using TG-61 should be highlighted, the microDiamond sensitive volume is significantly smaller than the typical ion-chambers used in TG-61 and consequently the back-scatter values used are an overestimate and their associated uncertainty should be expanded, quoted as 1.5 % in TG-61. In addition the irregular and small synchrotron field size meant that the data in TG-61 had to be extrapolated to a field with an equivalent area. The assumption that the stem correction is unity is also significant, as such the stem correction uncertainty is potentially greater than 1 %. Finally, in the keV range the Monte Carlo derived depth dose correction is sensitive to the thickness of the scoring volume used close to the surface, due to the small build up region where the dose is quickly varying with depth. Although a scoring volume with a thickness of 1 mm was used, the uncertainty on the depth dose correction would increase the uncertainty on the calorimeter derived $D_{w, 0cm}$. If the uncertainty on the calorimeter derived dose value is expanded to include a 0.5 % contribution, due to the depth dose correction for an overall uncertainty of 1.0 %, and the diamond-based uncertainty considered to be the TG-61 recommended uncertainty of 3.5 %, then both values agree within uncertainties at k=1 for all energies. This is despite underestimating the uncertainty on the microDiamond derived values.

The result highlights the limitations of using standard clinical protocols for synchrotron beams justifying the development of new standards and measurement protocols.

6.3 Determining The Dose Area Product

The dependence of $D_{w, 2cm}$ on the fluence distribution is not ideal, particularly since that distribution cannot be easily reproduced once the monochromator beam energy
is changed. Additionally, the procedure by which the fluence distribution is modeled involves taking careful film measurements with delayed readout and a non-trivial procedure to adequately fit and sample the resulting distribution in EGSnrc. These limitations present an obstacle for using the calorimeter to provide an instantaneous measurement of $D_{w, 2cm}$.

To circumvent the sensitivity to the beam profile the dose area product, DAP, is considered. DAP can be defined as the product of the average dose and the field size at a given depth. In this context the field size is defined by the collimator and aluminum core as 3.6 x 0.1 cm. The DAP is evaluated at a depth of 2 cm in a water phantom at the same distance from the primary collimator as the center of the calorimeter core. In order to derive the DAP, $k_w$ is replaced with $k_{DAP}$ in equation 6.1, where $k_{DAP}$ is defined as:

$$k_{DAP} = k_{B,A} k_{C,B} k_{E,C} k_{F,E} \quad (6.3)$$

Both $k_{B,A}$ and $k_{C,B}$ are independent of the fluence distribution used to model the source and were previously discussed. Simulation results for $k_{DAP}$ are shown in table 6.5. $k_{E,C}$ converts the dose scored in the calorimeter core, made up of water, to a truncated core with lateral dimensions equal to the collimated field used to determine the DAP, 3.6 cm. The major contributor to this correction is the reduction in the core mass, resulting in an increase in the dose on the order of 10% for all energies. This is due to minimal energy deposition in the regions shielded by the collimator, i.e. $>1.8$ cm laterally away from the central axis. While this correction is dependent on the divergence of the beam, it is independent of the source fluence distribution. Since the synchrotron beam is practically parallel, the correction is insensitive to positioning uncertainties, with a 5 cm change in the position (along the beam direction) of the
Table 6.5: Components of $k_{DAP}$ based on the simulations in figure 6.1.

<table>
<thead>
<tr>
<th>E (keV)</th>
<th>$k_{E,C}$</th>
<th>$k_{F,E}$</th>
<th>$k_{DAP}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>83</td>
<td>1.108</td>
<td>1.002</td>
<td>0.469</td>
</tr>
<tr>
<td>100</td>
<td>1.108</td>
<td>1.002</td>
<td>0.627</td>
</tr>
<tr>
<td>115</td>
<td>1.107</td>
<td>1.002</td>
<td>0.745</td>
</tr>
<tr>
<td>140</td>
<td>1.107</td>
<td>1.002</td>
<td>0.885</td>
</tr>
</tbody>
</table>

phantom relative to the primary collimator resulting in a 0.1 % effect on $k_{E,C}$.

$k_{F,E}$ then calculates the conversion to an identical core geometry centered at a depth of 2 cm but with a 0.05 cm dimension along the direction of the beam. $k_{F,E}$ is a measure of volume averaging in the beam direction, a correction on the order of 1.002. The minimal volume averaging in the beam direction is a consequence of the depth of measurement in phantom, well beyond the region of secondary charged particle build-up, where the variation in secondary particle fluence would result in significantly larger corrections.

A $k_{DAP}$ correction between 0.469 and 0.885 is derived. The uncertainty on $k_{DAP}$ is expected to be 0.6 %, which is smaller than $k_w$ due to the insensitivity to the beam profile used for the source to derive the correction. An uncertainty budget to derive the DAP using the second calorimeter prototype is shown in 6.6.

A beamline user can use the calorimeter to evaluate the DAP using equation 6.4. Since $k_{DAP}$ is independent of the beam profile the values shown in table 6.5 can be used. The calorimeter should be setup at a distance of 1.2 m, from the front face of the calorimeter window to the rear of the primary collimator. Equation 6.4 then provides the DAP at a depth of 2 cm in a water phantom, at a collimator to phantom surface distance of 1.233 m, with an overall uncertainty of 0.82 %. Although a disadvantage of determining the DAP is the inability to derive dose to a point nevertheless the
Table 6.6: An uncertainty budget based on the determination of DAP using the second prototype.

<table>
<thead>
<tr>
<th></th>
<th>Type A (%)</th>
<th>Type B (%)</th>
<th>Combined Unc. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature Rise</td>
<td>0.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermistor Calibration</td>
<td></td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>$k_{ht}$</td>
<td></td>
<td>0.50</td>
<td></td>
</tr>
<tr>
<td>$k_{DAP}$</td>
<td>0.01</td>
<td>0.60</td>
<td>0.82 (k=1)</td>
</tr>
<tr>
<td>Aluminum Specific Heat Capacity</td>
<td>0.12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Positioning</td>
<td>0.05</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DAP</td>
<td></td>
<td></td>
<td>0.82 (k=1)</td>
</tr>
</tbody>
</table>

quantity is commonly used in synchrotron dosimetry investigations. Particularly since DAP is a measure of the average dose over the beam area, and would be useful to investigations where only the average dose is desired [3, 4, 146].

$$DAP \left[ Gy \cdot cm^2 \right] = c_{Al} \Delta T k_{ht} k_{DAP} [3.6 \ cm \times 0.1 \ cm] \quad (6.4)$$

6.4 PTW microDiamond Absorbed Dose Calibration

For routine experiments at the CLS the use of a calibrated detector to give a real-time measurement of $D_{w, 2cm}$ would be useful and provide a notable improvement over various ion chamber based methods to estimate the absorbed dose. A detector other than the calorimeter would simplify the measurement procedure at the expense of a larger overall uncertainty. The use of a microDiamond detector has been successfully demonstrated for the range of energies and dose rates used in this work, in chapter
5.4.2.

By placing the diamond in an edge-on orientation, figure 5.2, at a distance of 1.00 ± 0.05 m from the primary collimator in air, the charge collected can be related to \( D_{w, 2cm} \) using an absorbed dose calibration factor, \( N_{D, w}^{E} \) where \( E \) denotes the beam energy. Equation 6.5 defines \( N_{D, w}^{E} \) as a function of \( D_{w, 2cm} \) and the diamond charge reading \( M_{dia} \). Performing the microDiamond measurement in air was deemed simpler to a measurement performed in a water phantom, particularly when considering the relative insensitivity to positioning in the beam direction.

\[
N_{D, w}^{E} = \frac{D_{w, 2cm}}{M_{dia}} \tag{6.5}
\]

Measurements performed using the calorimeter and microDiamond for the same "calibration beam", can then be used to derive \( N_{D, w}^{E} \) at each beam energy. In the absence of the calorimeter the diamond can be used along with the previously determined \( N_{D, w}^{E} \) values to determine \( D_{w, 2cm}^{User} \), in a user beam. It should be emphasized that the derived \( N_{D, w}^{E} \) values are unique to the particular diamond detector used to measure \( M_{dia} \) and should not be used with another diamond detector, even one of an identical design. Differences in the response of identical detectors are common and can often be attributed to the lack of reproducibility in the detector manufacturing process. For the microDiamond, variations in the thickness of the active volume (the diamond crystal), have been reported in the literature and are a concern [147].

Based on the charge measurements collected by the microDiamond in table 5.5 and the corresponding calorimeter measurements using the second prototype, \( N_{D, w}^{E} \) calibration factors can be derived, table 6.8. The calibrated microDiamond can then be used to determine \( D_{w, 2cm}^{User} \) in the absence of the calorimeter using equation 6.6.
Table 6.7: An uncertainty budget based on the determination of $N_{D,w}^E$ using the second prototype and microDiamond.

<table>
<thead>
<tr>
<th></th>
<th>Type A (%)</th>
<th>Type B (%)</th>
<th>Combined Unc. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_{w,2cm}$</td>
<td>0.89</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$M_{dia}$</td>
<td>0.30</td>
<td>0.30</td>
<td></td>
</tr>
<tr>
<td>$N_{D,w}^E$</td>
<td></td>
<td></td>
<td>0.99 (k=1)</td>
</tr>
</tbody>
</table>

Table 6.8: Measured microDiamond, s/n 122352, $N_{D,w}^E$ values using the second calorimeter prototype.

<table>
<thead>
<tr>
<th>E (keV)</th>
<th>$M_{dia}$ (nC/s)</th>
<th>$D_{w,2cm}$ (mGy/s)</th>
<th>$N_{D,w}^E$ (mGy/nC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>83</td>
<td>1.08</td>
<td>913</td>
<td>845 ± 1</td>
</tr>
<tr>
<td>100</td>
<td>0.633</td>
<td>510</td>
<td>806 ± 1</td>
</tr>
<tr>
<td>115</td>
<td>0.337</td>
<td>267</td>
<td>792 ± 1</td>
</tr>
<tr>
<td>140</td>
<td>0.091</td>
<td>68.6</td>
<td>754 ± 1</td>
</tr>
</tbody>
</table>

$$D_{w,2cm}^{User} = M_{dia}^{User} N_{D,w}^E$$  \hspace{1cm} (6.6)

Where, the appropriate calibration factor, $N_{D,w}^E$, can be found in table 6.8 and $M_{dia}^{User}$ denotes the charge collected using the diamond in an edge-on orientation in air, at a distance of 1.00 ± 0.05 m from the primary collimator.

When the monochromator settings are changed, it is not possible to precisely deliver an identical beam profile to the calibration beam. The assumption in using $N_{D,w}^E$ to derive $D_{w,2cm}^{User}$ for a user beam is that any variation in $M_{dia}$, would be due to variations in $D_{w,2cm}^{User}$. This is not strictly true, as different profiles will result in different scatter contributions to $D_{w,2cm}^{User}$ relative to $M_{dia}$. However, due to the small sensitive volume of the microDiamond this effect is minimized. Simulations performed
with a variety of different beam profiles indicated that the impact on $M_{\text{dia}}$ was less than 0.3 %, consequently a conservative estimate of 0.3 % was assigned as the type B uncertainty for $M_{\text{dia}}$. An overall uncertainty of 0.99 % is derived for $N_{D,w}^E$, table 6.7.

An overall uncertainty for the diamond measured $D_{w,2\text{cm}}^{\text{User}}$ of 1.03 % is derived based on the uncertainties of $N_{D,w}^E$ and $M_{\text{dia}}^{\text{User}}$ in table 6.9. Note the omission of the type B uncertainty on $M_{\text{dia}}^{\text{User}}$, which was used to account for the impact of beam profile variations and is implicitly accounted for in the uncertainty of $N_{D,w}^E$. The $N_{D,w}^E$ calibration factors should ideally be derived at least once a year, to be consistent with other external beam calibration procedures [17, 24].

**Table 6.9:** An uncertainty budget based on the determination of $D_{w,2\text{cm}}^{\text{User}}$ using the calibrated microDiamond.

<table>
<thead>
<tr>
<th></th>
<th>Type A (%)</th>
<th>Type B (%)</th>
<th>Combined Unc. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{D,w}^E$</td>
<td></td>
<td></td>
<td>0.99</td>
</tr>
<tr>
<td>$M_{\text{dia}}^{\text{User}}$</td>
<td>0.30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$D_{w,2\text{cm}}^{\text{User}}$</td>
<td></td>
<td>1.03 (k=1)</td>
<td></td>
</tr>
</tbody>
</table>

### 6.5 Conclusion

In this chapter the Monte Carlo based conversion to determine the absorbed dose to water at a reference depth of 2 cm was presented using two different approaches. The $D_{w,2\text{cm}}$ was determined with an uncertainty of 0.89 %. To circumvent the dependence of $D_{w,2\text{cm}}$ on the beam profile and improve the usability of the calorimeter for daily use the DAP was derived, at a depth of 2 cm for a 3.6 cm $\times$ 0.1 cm beam area, with an uncertainty of 0.82 %. Additionally, a simple application of the TG-61 protocol showed agreement between microDiamond and calorimeter derived $D_{w,0\text{cm}}$ estimates.
at < 5 % within uncertainties. Despite this agreement the procedure highlights the limitations of using standard clinical protocols for synchrotron beams.

A series of calibration factors have also been derived to allow a beamline user to use the microDiamond detector to derive $D_{w, 2cm}$ with an uncertainty of $\sim 1.0 \%$. The determination of $D_{w, 2cm}$ at the 1 % level is a significant improvement over current dosimetry protocols used at the CLS. Air-kerma based procedures investigated at the beginning of this work using CLS provided nominal air-kerma rates had uncertainties on the order of 10 %, which would be expected to increase for conversions to $D_{w, 2cm}$.

The determination of the absorbed dose to water at depth with an uncertainty below 1 % is a significant improvement over previous investigations at different light sources presented in the literature review. Use of monochromatic beams eliminated any Monte Carlo uncertainty components arising from uncertainty in determining the energy spectra, the approach can nevertheless be applied to a poly-chromatic beam. Even considering the reduction in uncertainty due to the use of a monochromatic beam the results provide a substantial improvement and show the advantages of using a purpose built calorimeter design.
Chapter 7

Conclusion

7.1 Overview of Results

The unique properties of synchrotron x-rays, including beam energy, dose-rate and collimation make them potential research tools for studying novel radiotherapy treatment modalities such as MRT, Microbeam Radiotherapy, and FLASH, the observed sparing of normal tissues from radiation damage when exposed to high dose rate beams (>40 Gy/s). In addition, the ability to produce monochromatic x-ray beams allows the energy dependence of radiation detectors to be precisely characterized. To provide a strong dosimetric basis for such investigations, the goal of this work has been to measure the absorbed dose to water at a depth of 2 cm due to monochromatic beams in the 80-140 keV range with a lower uncertainty than current methods.

To achieve this, a purpose built calorimeter was developed. The unique design was thoroughly assessed using thermal FEM simulations and MC radiation transport simulations. A first prototype was built and preliminary irradiations at the Canadian Light Source, CLS, confirmed the feasibility of the approach. The feasibility was
assessed by measuring the absorbed dose to aluminum in air with an estimated uncertainty of 0.84%. Several modifications were then made to the design and a second prototype was constructed resulting in a marginal improvement in the uncertainty on the absorbed dose to aluminum in air 0.75%, although with greater confidence in this uncertainty estimate. Consistency between both prototypes was demonstrated at < 1.5%. Additionally both the long term and short term reproducibility of the calorimeter’s performance was confirmed including the robustness of the design.

A preliminary validation was performed where the CLS air-kerma rate measured using the second prototype was compared to the air-kerma rate measured using a calibrated microDiamond detector for monochromatic synchrotron beams in the 80-140 keV range. Air-kerma values agreed at <1.5 % for all energies, well within uncertainties, serving as an initial confirmation of the approach.

Monte Carlo based conversion to the quantity of interest, $D_{w, 2cm}$, was outlined in chapter 6. A overall uncertainty of 0.89% was derived, substantially lower than current methods, typically between 5-10% at the CLS. In addition, a procedure to derive the Dose Area Product, DAP, was outlined to reduce the dependence on beam profile variation. An overall uncertainty of 0.82% for the DAP was consequently derived. Finally, to facilitate routine operation and future research investigations at the CLS Bio-Medical Imaging and Therapy Insertion Device beamline, BMIT-ID, a microDiamond detector was calibrated and a measurement protocol to derive, $D_{w, 2cm}$, using the microDiamond in the absence of the calorimeter outlined. An overall uncertainty on the calorimeter calibrated microDiamond determination of $D_{w, 2cm}$ of 1.03% was derived.

In conclusion the new calorimeter has been shown to accurately determine the quantity of interest, $D_{w, 2cm}$, with a substantially lower uncertainty than current
methods. Routine use of the calorimeter has been demonstrated, and will provide a new more accurate dosimeter for synchrotron users in Canada and potentially at other synchrotrons internationally.

### 7.2 Future Work

For a thorough validation of the measurement approach a comparison with another standard is required. A Free Air Chamber (FAC) is ideal, as FACs currently provide the lowest uncertainty on x-ray air-kerma measurements. Agreement within uncertainties would then provide a thorough validation of the calorimeter.

A natural next step would be an attempt to measure the absorbed dose due to a synchrotron produced 'white' beam. White beams have dose rates orders of magnitude greater than the monochromatic beams measured in this work. The resulting larger temperature rise would be less sensitive to noise and consequently be more reproducible. To maintain the low uncertainty of the calorimeter measurement of absorbed dose derived in this work accurate knowledge of the white beam spectrum is required. Deriving the synchrotron energy spectrum, either analytically or through measurement, is not trivial. However, using detailed knowledge of all beamline components other investigations have demonstrated the feasibility of estimating a synchrotron white beam spectrum [148].

The calorimeter is not necessarily limited to the beam energy and beam size used in this investigation but there are certain limitations. The small mass of the core, and subsequent conduction correction, requires short irradiation times, and therefore limits the minimum dose rate measurable. The data obtained here suggest, with suitable data acquisition and improved electrical noise isolation, that dose rates down to 1 Gy/min
may be achievable while maintaining an overall uncertainty less than 1%. Large field sizes, particularly a field impinging on the outer vacuum vessel (radius 4 cm) will introduce significant scatter contributions and result in increased energy deposition in the thermistor, impacting both $k_{\text{vessel}}$ and $k_{\text{ht}}$. However, operation in another beam modality is attractive as a simpler validation method than comparison with another synchrotron beam primary dose standard such as the FAC described. Given the low dose rates of conventional x-ray tubes a comparison with a FAC is only feasible in a synchrotron beam. Depending on the specific beam in question, operation in ultra high dose rate beams, as designed for FLASH dose delivery, should be possible. The portability of the calorimeter, for operation at clinical and research sites, has already been demonstrated and FLASH dose rates should result in very short irradiation times, further improving the reproducibility of the measurement. Collaborating with CLS staff on the routine use of the calorimeter and further development of a measurement protocol for beamline users will be investigated.
Appendix A

The EGSnrc Source Model

The non-uniformity in the beam profiles measured, figure 3.2, are not adequately described by any of the preset source types provided by EGSnrc. A custom source was therefore created to reproduce the measured film profiles.

Figure A.1: A simulation showing the effect of the *EGScollimatedsource*, when a point source is collimated onto a rectangle shape. The photon tracks are shown in red and the collimated shape represented by the black dashed line.
To fully describe a photon beam the energies and directions of its constituent photons need to be determined. The **EGS_collimated** source, is a source preset in EGSnrc that selects particles emitted isotropically from a point source that are incident on a target shape typically defined by a collimator, illustrated in figure A.1 for a rectangular target. Each photon incident on the rectangle maintains its original divergence. Points are sampled uniformly within the rectangle and for each sampled point a photon is generated from the source that follows a vector ending at the sampled point.

![Figure A.2](image)

**Figure A.2:** The 6th degree polynomial fit, of the 140 keV film profile at 3.7 T used to generate an EGSnrc representation of the synchrotron source. The dotted line is representative of the vertical profile of the source used in the simulation, for that beam energy.
If a ‘shape’ is defined such that the distribution of sampled points matches the measured film distribution and the point source is placed at a distance equivalent to the position along the beamline at which the film measurements were performed, 55 m, the synchrotron beam can be accurately described. To achieve this a 6th degree polynomial is fitted to each normalized profile. The 6th degree polynomial, shown in figure A.2 is used to calculate the normalized intensity in increments of 0.001 mm. A probability, at each 0.001 mm increment, is derived by dividing the normalized intensity by the sum of normalized intensities for all points. A cumulative probability function can then be derived. The procedure is summarized below, where \( P(x_i) \) and \( C(x_i) \) denote the probability and cumulative probability at position \( x_i \).

\[
P(x_i) = \frac{I(x_i)}{\sum_i I(x_i)}
\]

\[
C(x_i) = P(x_i) + C(x_{i-1})
\]  \( (A.1) \)

\( C(x_i) \) values are generated for each profile in increments of 0.001 mm, and saved as a discrete list. By sampling a uniform random number on \([0,1]\) and matching the closest cumulative probability function value in the discrete list and returning its location in the list, then the corresponding position will be sampled with a probability proportional to the signal intensity measured by the film. For a horizontal profile, where the method is applied from -20 mm to +20mm, the position can be derived as:

\[
x[mm] = (\text{list position}) \times 0.001[mm] - 20[mm]
\]  \( (A.2) \)

It should be noted that using the EGS\textunderscore collimated source in this way is not strictly accurate. Since the profiles used were experimentally measured, all points on the profile
should have equal statistical weight in the simulation. However, \textit{EGS\_collimated} source decreases the statistical weight of particles away from the center of the shape used to collimate the source. This is valid in the case of figure A.1. Given that the source is located at least 55 m away, the beam is practically parallel when it reaches the defined shape, the increased statistical weight would then be insignificant allowing the profile to be accurately reproduced. For completeness a simple derivation is shown in figure A.3.

Both horizontal and vertical profiles are independently sampled to generate the full distribution of source photons. For each beam simulated a new source is compiled

\[
w_i = \frac{\hat{u}_i \cdot \hat{n}_0}{r_i^2}
\]

\[
w_0 = \frac{1}{r_0^2}
\]

\[
w_1 = \frac{\cos(\theta)}{r_1^2 + 0.04^2} = \frac{r_0}{\sqrt{(r_0^2 + 0.04^2)^2}}, \text{ for } (r_0^2 > 0.04^2)
\]

\[
w_1 = \frac{1}{r_0} = w_0
\]

\textbf{Figure A.3:} \textit{A simple derivation showing that the statistical weights of generated photons using the EGS collimated source are identical.} \(\hat{n}_0\) denotes the surface normal unit vector, \(\hat{u}_i\) the photon direction, \(w_i\) the statistical weight of a photon. The weights are shown to be identical for photons generated along the central axis and the field edge.
and used to match the experimentally measured profile and used for all simulations involving that beam.
Appendix B

Calorimeter Readout Program

A python based script was implemented with the goal of automating the calorimeter readout procedure. The main goal of the program is to identify the beginning and end of each irradiation from a single temperature trace encompassing multiple irradiations. Once the beginning and end of each irradiation is identified the pre- and post-irradiation temperature traces are linearly fitted and extrapolated to the irradiation midpoint.

A sample irradiation temperature trace is shown in figure B.1, for the lowest dose rate 140 keV beam. If one considers that the time between irradiations is significantly larger than the irradiation time, approximately 60 s versus a 15 s irradiation time, then the instantaneous rate of change of temperature $\frac{dT}{dt}$, during an irradiation would be greater than 2 standard deviations of the mean of $\frac{dT}{dt}$ for all points.

If one selects all points where $\frac{dT}{dt} > 2\sigma$ and then computes the time difference between successive points the resulting data can expressed in a list as shown below for figure B.1:
The list is shown above on multiple lines for ease of presentation, and is not meant to represent a matrix. The first entry in the list shows that there are 55 sample points between the current sample and the next sample with $\frac{dT}{dt} > 2\sigma$, the next series of points show that successive samples satisfy $\frac{dT}{dt} > 2\sigma$ indicating the beginning of an

\[
\begin{pmatrix}
55 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 & 2 & 1 & 1 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 181
\end{pmatrix}
\] (B.1)

**Figure B.1:** A sample 140 keV irradiation temperature trace measured using the first calorimeter prototype.
irradiation. Using the same reasoning the final point in the list, implies the end of an irradiation. One can relax the condition of what defines successive runs, for example considering points separated by less than 3 samples as the threshold for a successive run. In doing so the algorithm becomes less sensitive to the influence of noise.

The result of analyzing the trace shown in figure B.1 is shown in figure B.2. Vertical lines indicate the bounds used to apply the linear fits shown. The linear fits are additionally extrapolated to the irradiation midpoint.

By multiplying the average temperature rise for multiple irradiations by the appropriate corrections described in chapters 3-6 both air-kerma and absorbed dose

![Figure B.2: A sample 140 keV irradiation temperature trace measured using the first calorimeter prototype after being processed using the calorimeter readout program.](image)
Figure B.3: A sample terminal output using the calorimeter readout program for a series of 140 keV irradiations using the first prototype.

estimates can be derived in real time. A sample terminal output is shown for a series of 140 keV irradiations in figure B.3.
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