Characterisation of a Graphite Calorimeter in Scanned Proton Beams

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Abstract

The NPL graphite proton calorimeter is used to measure the dose deposited from irradiation by proton beams. This thesis describes the first measurements carried out with the calorimeter in proton pencil beams as well as an analysis of the calorimeter data in scanned proton beams. In doing this analysis, a greater understanding of the response and heat flows within the calorimeter was achieved. These measurement results are compared to simulations carried out using COMSOL Multiphysics®, a finite-element simulation software package. A model of the calorimeter was built in TOPAS, a Monte Carlo platform which wraps and extends the GEANT-4 simulation toolkit. This model was used to calculate two correction factors: the gap correction factor, which increased with energy from 1.00064(08) at 60 MeV to 1.00359(15) at 230 MeV; and the volume averaging correction factor which was 0.99936(44) at 60 MeV and 1.00515(154) at 230 MeV. TOPAS was also used to build a model of the Clatterbridge beamline, producing Bragg peak and modulated depth-dose curves for the 62 MeV proton beam. This can be used for future, more detailed investigations and coupled TOPAS/COMSOL simulations.

Key words: Medical Physics, Proton Therapy, Dosimetry, Graphite Calorimetry, Primary Standards, Scanned Proton Beams.

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Glossary

**Absorbed Dose** the mean energy deposited in a material by ionising radiation per unit target mass; the fundamental dose quantity.

**Apoptosis** the active biochemical process of programmed cell death.

**Chemical Heat Defect** the ratio of the net energy consumed by chemical reactions following the radiolysis of water by ionising radiation to the energy imparted.

**COMSOL** a software package for modeling and simulation of physical processes. N.B. the name is not an acronym but was inspired by a contraction of ‘computer simulation’.

**Distal** anatomical term, referring to something beyond the point of interest (further away from the observer).

**Effective Dose** the equivalent dose weighted by tissue type.

**Equivalent Dose** the absorbed dose weighted by radiation type.

**Fluence** the number of particles passing through a medium per unit area.

**Free Radical** a highly reactive atom, molecule or ion.

**Gray (Gy)** the restricted usage name for the SI unit of absorbed dose.

**Isocentre** For a rotating gantry: the point (or small volume) that the beam will pass through at any gantry angle. For a fixed gantry: refers to a nominal isocentre, a point along the beam axis chosen such that the beam is in focus.

**Ocular Melanoma** a cancer of the eye occurring in cells which produce the pigment melanin.

**Penumbra** the region at the edges of a radiation beam where the dose decreases (falls off) from its maximum.

**Perspex (and Lucite)** tradenames for polymethyl methacrylate (PMMA).

**Physiochemical** relating to physics and chemistry.
**Proximal** anatomical term, referring to something nearer than the point of interest (closer to the observer).

**Radiolysis** the breaking of chemical bond(s) due to high energy radiation.

**Reference Dosimetry** dosimetry carried out under reference conditions.

**Stochastic Distribution** a nondeterministic or random distribution.

**Stopping Power** the rate of loss of kinetic energy for a single proton.

**Target Volume or Region** anatomical volume to be irradiated, usually encompassing the tumour itself and some surrounding tissue for uncertainty margins.

**Uveal Melanoma** a subset of ocular melanomas, occurring in the iris, ciliary body or choroid.

**Voxel** a 3D volume element.
Acronyms

AAPM The American Association of Physicists in Medicine.


CCC Clatterbridge Cancer Centre (formerly known as CCO).

CCO Clatterbridge Centre for Oncology.

DD Depth dose (usually referring to a depth dose curve).

ESTRO European SocieTy for Radiotherapy and Oncology.

FEMLAB Finite Element Modeling LABoratory.

FWMH Full Width Half Maximum.

GEANT4 GEometry ANd Tracking version 4.

IAEA International Atomic Energy Agency.

ICRU International Commission on Radiation Units and Measurements.

IMPT Intensity Modulated Proton Therapy.

Kerma Kinetic Energy Released (by ionising radiation) per unit MAss.

MC Monte Carlo (simulations).

MCS Multiple Coulomb Scattering.

MU Monitor Unit.


NPL National Physical Laboratory.

PBS Pencil Beam Scanning.
Acronyms

PCB  Printed Circuit Board.
PCRD  Practical Course in Reference Dosimetry.
PDD  Percentage Depth Dose (a normalised depth dose curve).
PGBioMed  Postgraduate Conference on Biomedical Engineering and Medical Physics.
PGR  Postgraduate Research.
PMMA  Polymethyl methacrylate.
PPRIG  Proton Physics Research Implementation Group.
PSDL  Primary Standard Dosimetry Laboratory.
PSI  Paul Scherrer Institute.
PTCOG  Proton Therapy Co-Operative Group.
RBE  Relative Biological Effectiveness.
SI  French: “Système International”, the international system of units.
SOBP  Spread Out Bragg Peak.
SS  Spot Scanning.
TOPAS  TOol for PArticle Simulation.
UCL  University College London.
Chapter 1

Introduction

Over 350,000 people in the UK were diagnosed with cancer in 2013 [1] (the latest statistics available), and it is estimated that more than 50% of the UK population born after 1960 will develop cancer at some point in their life [2]. As cures and better treatments for various diseases are found, and populations are living longer, cancer is becoming more prevalent (89% of cancer incidences in the UK were in those aged over 50 [3]). It is therefore vital that current methods of cancer treatment are optimised, and that more research into newer treatments is carried out to ensure that the most effective methods are being used.

Currently surgery, chemotherapy and radiotherapy are the main cancer treatment modalities, with most patients receiving a combination of two or more methods. In the UK 39% of cancer patients undergo radiotherapy as part of their cancer treatment, however this is limited by capacity and would optimally be 52% [4].

Radiotherapy uses beams of radiation which ionise atoms to damage the DNA within cells, with the aim of inducing apoptosis (programmed cell death). In external beam radiotherapy the beams are produced outside the body and then directed towards the patient, passing through healthy tissue as well as the target region. The dose received by healthy tissue is minimised to avoid damaging organs and to reduce the risks of inducing secondary cancers [5]. There are many methods of reducing healthy tissue exposure; one simple example is using multiple beam angles so the surrounding tissue is given a lower dose than the cumulative dose received by the tumour.

This thesis focuses on a type of radiotherapy using protons rather than the con-
1.1 Overview of Thesis

This thesis presents research into the direct measurement of the dose delivered by scanned proton beams. This dosimetry is achieved using a graphite calorimeter, an instrument which works on the principle of measuring the changes in temperature from energy deposition by ionising radiation. In order for this to be achieved experiments have been done using both static proton pencil beams both centred and offset from calorimeter core, as well as a scanned proton beam looking at one, two and three-dimensional irradiation plans. The results have been compared to a simulated model of the calorimeter in COMSOL Multiphysics® [1]. In addition, Monte Carlo simulations have been run in TOPAS [2] for the purposes of obtaining a better approximation to the physical proton beam and calculating calorimeter correction factors.

This thesis summarises the theoretical knowledge necessary to understand the ba-
1.1. Overview of Thesis

ics of scanned proton beam calorimetry, including information on the interactions of protons with matter (section 2.1), a history of proton therapy (section 2.2.1), an explanation of the terms used in conjunction with scanned proton beams (section 2.2.5), a definition of absorbed dose (section 3.2), an introduction to calorimetry (section 3.3) and a detailed explanation of the structure of the NPL proton graphite calorimeter (section 3.4). The literature in this field has been reviewed and incorporated into the relevant sections, although since the implementation of scanned proton beams is in its infancy, there has been no peer-reviewed literature relating directly to graphite calorimetry in scanned proton beams.

Chapter 4 details the measurements taken and the data obtained in experiments using the graphite calorimeter in a static 60 MeV modulated proton beam at the Clatterbridge Cancer Centre as well as describing how the resulting data were analysed. It also explains a theoretical model of the thermodynamic transport properties of the NPL proton calorimeter created in a heat flow simulation software package called COMSOL Multiphysics, and the comparison between the temperature distribution results obtained when proton irradiation was simulated and the measured data.

Chapter 5 explains the COMSOL simulations of scanned beams and the results of an approximation to a scanned beam that was achieved in Clatterbridge. It also details the measurement data captured in the scanned proton beam at the Proton Therapy Center, Prague, looking initially at a similar set-up to Clatterbridge with static spots and moving on to line scans, a layer and ‘cube’ irradiations, looking at the effect of the scanned beam delivery on the response of the calorimeter.

Chapter 6 describes the simulation results of two Monte Carlo calculated correction factors: the compensated gap correction factor and the volume averaging correction factor. These were calculated using TOPAS, a simulation package designed especially for proton therapy.

This thesis provides a full characterisation of the NPL graphite calorimeter in scanned proton beams, and is part of an ongoing NPL project into developing a primary standard graphite calorimeter for dosimetry in proton therapy beams.
Chapter 2

Theory of Proton Therapy

Ionising radiation is the term given to particles which have enough energy (typically of the order of a few eV) to release a bound electron out of an atom or molecule (i.e. ionise the atom/molecule). Examples of such particles are high-energy photons, electrons, protons, neutrons and alpha particles, which can be produced either naturally (e.g. radioactive decay) or artificially (e.g. accelerators). This ionisation can disrupt chemical bonds (or in some cases, nuclear structure) and lead to the production of free radicals. These free radicals can damage DNA in cells which may then cause apoptosis. The aim of curative radiotherapy is to induce apoptosis in all cancerous cells and in as few healthy cells as possible.

2.1 Interactions of Protons with Matter

When a (positively charged) proton passes into matter it interacts primarily via the Coulomb force with the (negatively charged) atomic electrons and (positively charged) nuclei. The interactions with the electrons cause the proton to lose kinetic energy (referred to as stopping), while the interactions with the nuclei cause the proton to be deflected off its original path (referred to as scattering). In addition, the proton may also collide with the nuclei and cause nuclear interactions, although these occur

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1 A simplification: different atoms have different ionisation energies; particles are unlikely to transfer all of their kinetic energy to electrons; and in the case of neutron capture, a low energy neutron may produce ionising particles.
2.1. Interactions of Protons with Matter

much less frequently than electromagnetic interactions. These three interactions are described in more detail in sections 2.1.1, 2.1.2 and 2.1.3. The energy deposited in matter through interaction with ionising radiation is dissipated in the form of changes in physical state, chemical reactions and heat. If the absorber is chosen correctly then the physical and chemical changes are negligible, so the energy is (ultimately) dissipated as heat which leads to a rise in temperature of the absorber, and forms the theoretical basis for the calorimeter, an instrument used to measure this temperature rise (see section 3.3). Note that the temperature rises in a radiotherapy treatment are imperceptibly small, and it is the large biological effect of the radiation that damages cells in the body.

Stopping and scattering are both well understood and can be described mathematically with great accuracy, although the nuclear interactions are much less easy to characterise. However, they occur fairly infrequently and often simple approximations are sufficient. In this thesis, nuclear interaction cross sections are built into the GEANT4 [10] code, and experimentally measured beam data were used for the finite element simulations.

2.1.1 Stopping

The electromagnetic interactions with the electrons cause the kinetic energy of the protons to decrease following collisions with these negatively charged particles, thus the protons will slow down quasi-continuously as they travel along their paths. However, near the end of the proton’s path, its kinetic energy is low, so it interacts more frequently losing energy through these recurrent interactions. Therefore as the proton’s kinetic energy decreases, the rate of energy loss increases.

The rate of decrease of energy of a proton with depth is known as the stopping power ($S_{el}$). The slower the proton is moving, the more likely it is to interact with an electron (due to its increased collision cross section); and the more linear momentum the proton transfers to the electrons, the more kinetic energy it loses, so the stopping power increases.

The Bethe-Bloch equation for charged particles in matter, derived in 1933 [11], describes the stopping power theoretically. It can be modified for protons with energies
2.1. Interactions of Protons with Matter

Figure 2.1: Proton dose deposition as a function of depth in water. Data from measurements made with an ion chamber in a water phantom in a 60 MeV proton beam.

between 3-300 MeV to give equation 2.1

\[ S_{el} \equiv -\frac{dE}{dx} = 0.3072 \frac{Z}{A} \rho \beta^2 \left( \ln \frac{W_m}{I} - \beta^2 \right) \left( \text{MeV cm} \right) \]  \hspace{1cm} (2.1)

where \( Z, A, \rho \) and \( I \) all refer to the target material and are (respectively) the atomic number, mass number, density, and the mean excitation energy. \( \beta = \frac{v}{c} \) where \( v \) is the velocity of the proton and \( c \) is the speed of light. \( W_m \) is given by:

\[ W_m = \frac{2m_e c^2 \beta^2}{1 - \beta^2} \]  \hspace{1cm} (2.2)

with \( m_e \) being the rest mass of an electron. Thus the stopping power is approximately inversely proportional to the square of the proton velocity. After correcting for density, materials with a lower \( Z \) (atomic number) have a higher stopping power than materials with a high \( Z \) (since low \( Z \) atoms have a mass that is closer to the proton mass).

The relationship between the stopping power and the proton velocity leads to the energy deposition increasing with depth, with most of the proton energy being deposited in the short distance just before they stop. The dose is highest in this region and the characteristic peak caused by this effect can be seen in Figure 2.1.

The region of high dose deposition at the end of the path is known as the Bragg
2.1. Interactions of Protons with Matter

peak\footnote{Named after William Henry Bragg who discovered the effect \cite{12}.} and its position depends on the initial kinetic energy of the proton. If a beam of incoming protons all have the same energy, they will all stop at approximately the same depth (with a standard deviation of approximately 1.2% due to statistical considerations \cite{13}), which is known as the range \cite{11}.

More accurately the range is usually taken to be the mean projected range, \( R_o \), which is the depth at which 50% of the protons that have not undergone nuclear interactions have stopped. When measured with a dosimeter, this is (approximately) equal to the point at which the distal dose (the dose beyond the Bragg peak) has dropped to 80% of its peak value \cite{14}.

The ranges (in water) required in proton therapy are between a couple of mm (for targets in the skin or eyes) to approximately 50 cm (to reach the deepest parts of the body), which correspond to energies between 10 MeV and 300 MeV.

The range can be determined mathematically by integrating the inverse mass stopping power (the stopping power divided by density) between the initial energy and the energy just before it stops (zero energy can not be used since the equation diverges at this point).

\[
R(E_{\text{initial}}) = \int_{E_{\text{final}}}^{E_{\text{initial}}} \left( \frac{S}{\rho} \right)^{-1} dE
\]

From this the total path length can be found, in units of g/cm\(^2\), which enables a scaling for different materials if their density is known. By integrating the Bethe-Bloch equation, the range is found to be approximately proportional to the initial proton energy to the power of 1.75, but this varies with energy and with material, so in practice measured range-energy tables are used.

The ionisation is proportional to the dose, however the biological damage depends not only on the number of ionisations but on the density of ionisation (i.e. number of ionisations per unit volume), so the biological effectiveness is even greater in the Bragg peak than might be intuitively assumed.
2.1.2 Scattering

The elastic interaction between the proton and the nuclei mainly deflects the proton laterally by a small angle, and the random combination of multiple deflections (known as multiple Coulomb scattering, or MCS) leads to a (almost) Gaussian distribution in the angular spread of the beam. The width of the (near) Gaussian can be predicted very accurately given the energy of the protons and the material and thickness through which the beam passes.

A Gaussian distribution can be described mathematically by the following formula (assuming the mean = 0 and $\sigma$ is the standard deviation):

$$y = \frac{A}{\sqrt{2\pi}\sigma^2} e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$

(2.4)

where the full width at half maximum is given by:

$$\text{FWHM} = 2\sqrt{2\ln(2)}\sigma \approx 2.35\sigma$$

(2.5)

This is important when working out what size of beam is needed to resolve two objects: for example if the target volume and a critical structure are only 5 mm apart, a beam with $\sigma < 4.25$ mm is needed to give the critical structure $< 50\%$ of the target dose.

The distribution is only approximately Gaussian due to the contribution of larger angle scatters and nuclear interactions but in general the distribution is the sum of multiple random deflections so, as would be expected from the central limit theorem, the statistical fluctuations combine to give a normal distribution, with a single scattering tail (comprising approximately 2% of the initial protons) [11].

The most comprehensive theory for predicting the exact form of the MCS distribution for any proton energy, scattering material and thickness is Moliere’s Theory [15, 16]; however, it is algebraically complicated. More widely used is Highland’s empirical formula [17] which gives a mathematical description of the scattering angle ($\theta_0$), and its dependence on the target thickness ($L$) and radiation length of the target material ($L_R$) that is nearly as accurate:

$$\theta_0 = \frac{14.1 \text{MeV}}{p\nu} \sqrt{\frac{L}{L_R}} \left[ 1 + \frac{1}{9} \log_{10} \left( \frac{L}{L_R} \right) \right] \text{rad}$$

(2.6)

where $p$ is the proton momentum and $\nu$ is the proton velocity. This only applies to thin targets (where the target thickness $< < \text{mean proton range}$) since otherwise the proton
speed would vary too much within the target. In contrast to stopping, materials with a higher Z scatter protons more than materials with a low Z.

2.1.3 Nuclear Interactions

While the interactions causing stopping and scattering of the protons can be adequately described by well-understood atomic processes, equations derived from the classical laws of physics cannot be used to reliably calculate nuclear interactions. Tabulated data must instead be used and as computing power increases, leading to the increased use of Monte Carlo dose calculations, the requirement for more accurate nuclear data also increases.

If a proton collides head-on with a nucleus in an inelastic collision, secondary reaction particles may be formed on the outgoing channel. If the proton breaks up the nucleus of the “target” atom, these secondaries may be protons, neutrons or the nuclei of residual light elements resulting from the nuclear spallation reaction, e.g. additional protons, neutrons, photons, alpha particles etc. They will have much lower energies than the original proton, and be scattered over large angles.

The dose from these secondary particles is mainly deposited within a short distance of the reaction site and over a small area. However, neutrons may travel further and deposit dose further along the track or beyond the Bragg peak. This dose is typically much lower than the proton dose. Nonetheless, in a clinical setting care must be taken as neutrons may be produced within the treatment line due to nuclear reactions within beam modification devices, which can contribute to the patient dose both within and external to the treatment volume.

Nuclear interactions are the only way the initial number of protons in the beam may decrease; the flux of protons near the end of the range is within 80% of that at the start. The importance of the nuclear interactions increases with proton energy, but is relatively small in the energy ranges used for proton therapy [18].

Nuclear interaction data from the ICRU Report 63 [18] for proton therapy has been incorporated into the Monte Carlo software TOPAS. The ICRU data were obtained by comparing nuclear model calculations with measurements to produce kerma coefficients and nonelastic proton cross sections.
2.2 Proton Therapy

2.2.1 Brief History of Proton Radiotherapy

The idea of treating cancer using beams of protons was first suggested by Robert Wilson in his paper “Radiological Use of Fast Protons” [19]. He described how new higher energy accelerators would produce protons with sufficient range to penetrate tissue to a depth comparable to the dimensions of the human body, and reviewed the properties of protons relevant to this goal. He also suggested the use of a “rotating wheel of variable thickness”, which is now known as a range modulator, to cover the whole of a large tumour.

Eight years later the first patient was treated using high energy protons at a research accelerator at the Lawrence Berkeley National Laboratory (LBL), and 30 patients were irradiated between 1954 and 1957 (as well as various mice, monkeys and dogs) [20]. Of the patients treated, 26 had advanced metastatic breast cancer and were treated by proton irradiation of the pituitary gland with a fixed beam while the patient was rotated (although the plateau region rather than the Bragg peak region was used due to uncertainty in the proton range). The total dose delivered to the patient was split over several sessions (a technique known as fractionation) although the study was limited by the amount of beam time available. The trial was not wholly successful: two thirds of the patients were diagnosed as terminal prior to treatment, and indeed most of them died. However, the author notes that two patients were “alive and doing fairly well eighteen months after irradiation” [21].

Proton irradiation was carried out in the following years at various research accelerators including the Gustaf Werner Institute (Sweden), which was the first centre to utilise the Bragg peak region and to implement Wilson’s idea of range modulation [22]. They also introduced magnetic beam scanning to spread out the proton beam - scanned beams are generally considered a modern technique, yet they were used before scatterers had even been developed [23, 24, 25]. However, the magnet system was difficult to manage accurately so collimators were used for beam shaping. In 1961, patient treatment started at the Harvard Cyclotron in collaboration with Massachusetts General Hospital, with over 700 patients treated between 1961 and 1975 [26, 27].
The concept of scanning the beam in three dimensions was developed in the 1970s and the first implementation of ‘proper’ beam scanning (where the dose is delivered spot by spot, as opposed to using magnets to deflect the protons but using a collimator for shaping, see section 2.2.5) was in 1980 in Japan. It was subsequently introduced at several other centres, and new proton therapy centres are opting more and more to include the modality. By 1988 there was a total of 9 centres treating patients using proton therapy across the US, Europe and Asia, all of them based at research laboratories.

The first hospital based proton therapy centre was at Clatterbridge, England, which started treating patients for tumours of the eye in 1989 using low energy (62 MeV) protons from a fixed beam line. In 1990 a hospital based proton centre was set up at Loma Linda University Medical Center in the US, which was the first centre with a gantry that could rotate around the patient and deliver the proton beam from any angle.

At the end of 2014 there were 45 protons centres in operation around the world, with more than 40 being planned or under construction, and over 110,000 patients had been treated using proton therapy.

### 2.2.2 Comparison with Conventional Radiotherapy

Protons and photons produce very different dose distributions due to the differences in both mass (photons being mass-less) and charge between the particles. Photons have a depth dose curve that shows a slight increase (build-up region) before falling off exponentially (as given by the Beer-Lambert law), while the proton dose is low for much of the depth before increasing to the Bragg peak, then dropping to zero dose, known as the fall-off region. These are illustrated in Fig. 2.2. As described earlier, the position of the proton peak is dependent on the beam energy. Also shown in Fig. 2.2 is a “spread-out Bragg peak” (SOBP) where multiple beams of different energies are used to cover the whole depth of a tumour.

It can be seen from Fig. 2.2 that proton radiotherapy has advantages over photon radiotherapy since, while giving an equal (and flatter) dose at the tumour site, it gives a lower dose to the healthy tissue both pre- and post-tumour (a property referred to
2.2. Proton Therapy

Figure 2.2: The relative differences in depth dose curves between protons and photons. Data for this diagram has been scaled from measurements in water using ionisation chambers.

as better dose localisation). This means that higher doses can be given to the tumour (resulting in a higher probability of destroying the cells) while not exceeding tolerances for the cells anterior to the tumour. In addition posterior cells receive negligible irradiation, which is important when the structures are critical (for example the spinal cord or optic nerve).

There are some situations in which proton therapy is undoubtedly superior to photon therapy; especially in cancers of the head and neck where it is imperative to minimise the dose to surrounding tissue. However, for many other cases the choice is more ambiguous, and there is not enough evidence about the possible problems caused by a low “dose bath” to other organs. Proton therapy is generally believed to be better for treating paediatric cases since the cells in a child’s body are growing and replicating faster so there is a higher risk of induced cancers, as well as a longer time for those tumours to manifest themselves.

The extent to which the advantages of the localisation justify the higher cost of proton therapy is debatable [33]. Over time the relative cost in comparison with conventional radiotherapy is reducing as proton therapy becomes more widespread, and
newer treatment techniques (e.g. pencil beam scanning) are giving even better tumour conformation, so it remains to be seen whether proton therapy becomes more cost effective than current treatments.

2.2.3 Range Modulation Wheels

Figure 2.3: An example of a range modulation wheel, top view (beam’s-eye view).

The SOBP can be achieved in practice using one of several mechanical methods, the most widespread of which are range modulations wheels. These work by interposing a spinning Perspex disc of variable thickness into the beam line - the thicker the material the beam passes through, the shorter the range of the beam. The wheel can complete a full rotation up to 2500 times per minute [34], so although instantaneously only an individual Bragg peak is formed, it can be considered as a continuous SOBP in comparison with time scales in radiotherapy. Fully modulated beams produce a (near) flat dose for the full depth. Figs. 2.3 and 2.4 show a similar range modulation wheel to that used in the experimental work described in Chapter 4, with 4 symmetrical

\[^{1}\text{N.B. figures 2.3 and 2.4 show a modulation wheel with 20 steps, which produces a partially modulated beam.}\]
sections or “blades”.

Once a SOBP has been obtained, a bolus or compensator may be used to account for the shape of the distal edge of the tumour and/or any inhomogeneities along the proton beam path (for example bone or air pockets) [35].

Figure 2.4: Side view of the same range modulation wheel shown in Figure 2.3 showing the steps on the wheel which produce the spread-out Bragg peak.

2.2.4 Scattered Proton Beams

In addition to spreading out the beam along the length of the tumour using a SOBP (the distal spread), the beam also needs to be spread out laterally (i.e. covering an area perpendicular to the beam) - this is achieved using either scattering or scanning.

Protons do not undergo many large angle scatters within tissue, due to tissue’s low $Z_{eff}$, so in the scattering method scattering foils (sheets of materials with high $Z$) are placed in the beam so larger deflections occur, leading to a wider Gaussian distribution [14]. This method has been widely used because it is relatively economical, simple and theoretically well understood. On the other hand, it is inefficient (to get a homogeneous dose over the tumour, only a small portion of the beam at the peak of the Gaussian curve can be used), and it requires unique brass collimators and range compensators.
2.2. Proton Therapy

to be made for each patient (which increases the neutron dose received).

To overcome the inefficiency, the double scattering technique was introduced \[36\] where two different materials are used and the materials are contoured \[37\] so the emerging beam has a flat distribution.

2.2.5 Scanned Proton Beams

In the scanning method, the beam is moved (either by mechanical or magnetic methods) to spread the dose over the target volume. A form of mechanical scanning can be achieved by moving the target in a fixed beam, which has been utilised in some of the experiments detailed in this thesis, or using an adjustable collimator to control what part of the beam is visible to the target. In magnetic scanning, magnets are used to deflect the charged proton beam horizontally and vertically. All of these methods reduce the number of neutrons produced within the beam line, and thus the extra neutron dose to the patient \[38\]. There are various different methods of magnetic scanning: uniform scanning (also known as “beam wobbling”), line scanning, raster scanning and pencil beam scanning (also known as “spot scanning”) \[11\].

Uniform Scanning

Uniform scanning replaces the scattering foils with deflecting magnets, to give a homogeneous dose over a large area, but then the rest of the process remains similar to the scattering method using collimators and compensators to control the shape and range \[39\]. Beam wobbling is similar to uniform scanning but the beam has been scattered slightly before being scanned to give a larger spot size.

Line Scanning

In line (or continuous) scanning, the beam moves continuously across the target cross sectional area; the speed of this motion may change, but protons are being emitted from the nozzle the entire time. In spot scanning the beam is turned on for a finite time at each voxel (a volume element, the 3D version of a pixel) to deliver the dose, but is turned off while the spot position is adjusted. The term ‘raster scanning’ has been used to describe both of these approaches - the variability in the definitions shows
how new the field is. The use of these two regimes depends on the particular setup at a specific facility e.g. the level of discreteness of motion possible, or the stability of the beam current.

**Pencil Beam Scanning (PBS)**

In the pencil beam scanning (PBS) method, the dose is painted over the target volume spot by spot, with the energy (and therefore range), position, size and intensity of the beam defined for each voxel. The term ‘pencil’ beam refers to its size: the beam may be unmodified from the beam line in which case the diameter can be of the order of millimetres, or it might be only slightly larger. A beam with diameter of a couple of centimetres may be referred to as a ‘crayon’ beam.

PBS eliminates the need for patient specific hardware, minimising secondary neutron dose, and can produce near perfect conformity to the tumour. The main disadvantage of this method is that the treatment time is longer due to the change over time between the different energies, although less time is taken during beam set up due to the lack of patient specific hardware [40]. However, the accuracy of this method leads to other problems: the uncertainties in organ position, proton range and errors due to organ motion are (relatively) more important, so larger tolerances for these factors need to be applied.

A SOBP may occasionally be used in PBS, but because of the delivery method it is possible to create a more specific dose distribution to better suit the target region. However, for small ranges (shallow depths), it can be difficult to get a smooth curve due to the narrow width of the Bragg peaks - in these cases a range shifter or other modifying device may be utilised. Generally the dose is delivered in layers, with each layer corresponding to a specific beam energy [41].

Note that although spot sizes are referred to, the distribution is determined statistically, so is not a perfectly smooth two-dimensional Gaussian - it only tends towards this for a large number of particles in the beam. This is especially important for spot scanning since one property of the Gaussian distribution which is often used is that a correctly positioned superposition of Gaussians will give a lateral distribution with a flat top. However, if the width of the bell curve is smaller than that for a Gaussian (as
may occur with a lower beam current), then the flat lateral distribution may not occur.

An even more advanced form of scanned beam proton therapy is Intensity Modulated Proton Therapy (IMPT) where each spot can deliver a different number of protons, creating fields of non-uniform intensity. Different fields can be delivered from different angles to further optimise the tumour-to-normal-tissue dose ratio. The treatment planning for this modality is much more complex than others, but it is ideal for complicated tumour volumes.

**Tumour Motion**

Strategies to reduce the influence of tumour motion include: using gating techniques which switch the beam on and off during the breathing cycle; repainting the target volume multiple times (averaging out any errors) - this requires either increasing the dose rate or using larger pencil beams so the time taken to scan the tumour is reduced; and tracking the target motion by imaging the tumour during treatment and adjusting the beam accordingly.

**Accelerators**

Accelerators for scanned proton beams can be much smaller than those using the scattering method because in the scattering method the protons lose energy as they pass through the scattering system and range modulation wheel, so the beam energy is much lower at the patient than it is when it comes out of the accelerator. In the scanning method, these energy losses are much lower, so the accelerator can be much smaller to produce the same beam energy from the nozzle. However, the accelerators need to be able to deliver beams with the necessary characteristics, varying the beam energy, position, spot size and intensity quickly enough to suit clinical needs.

### 2.3 Clatterbridge Cancer Centre

One of the proton beams used in experiments detailed in this thesis was located at the Clatterbridge Cancer Centre (CCC) NHS Foundation Trust in Wirral, Merseyside (formerly the Clatterbridge Centre for Oncology (CCO)). It is currently the UK’s only
proton treatment centre, having been commissioned for neutron therapy in 1984 and later adapted for ocular proton therapy, for which it treated the first patients in June 1989. A Scanditronix MC-60 PF cyclotron produces a fixed low energy, passively-scattered proton beam of 62 MeV which corresponds to a maximum range of 31 mm in water with a 0.9 mm fall-off. Beam scattering is produced by two tungsten scattering foils, each 20 µm thick. Approximately 100 patients with a specific tumour of the eye called uveal melanoma are treated at the CCC each year, with a 5-year local control rate of 97% [42].

The purpose of the Clatterbridge measurements was firstly to look at the effect on the calorimeter of irradiations with a narrow beam and secondly to use the narrow beam to irradiate not just the centre of the core but also at positions offset from the centre. Neither of these had previously been measured using the NPL calorimeter.

### 2.4 Prague Proton Therapy Center

The other proton beam used for the calorimeter measurements was the Prague Proton Therapy Center, Czech Republic, a new clinical cyclotron facility that started treating patients in December 2012 based on technology from the company IBA (Ion Beam Applications).

The significant difference between the Clatterbridge beam and the Prague beam is the maximum energy of the protons. While the Clatterbridge proton beam has a maximum energy of 60 MeV, the Prague beam has a maximum energy of 230 MeV, which corresponds to a maximum depth in water of approximately 34 cm, so despite the proton energy being less than 4 times higher, the range in water is over 10 times further. For some of the measurements in Chapter 5 the “raw” proton beam coming from the cyclotron had the beam energy reduced using a degrader.

The other important difference at the Prague centre is that the beam is a scanned proton beam, so the method of beam delivery and structure of the beam-line is significantly different from the Clatterbridge beam-line, with no collimator or modulator wheel in the path of the beam [43].
Chapter 3

Theory of Radiation Dosimetry

Radiation dosimetry is the measurement of the quantity or amount of radiation. There are many different “doses” referred to in radiation therapy, including absorbed dose, equivalent dose and effective dose. This thesis is concerned with absorbed dose, but for reference the equivalent and effective doses are related to the absorbed dose in the following way: equivalent dose is the absorbed dose weighted by radiation type, while effective dose is the equivalent dose weighted by tissue type [44]. Note that for clinical radiotherapy accelerators, the machine output is measured in monitor units (MU), the name coming from the monitor (ionisation) chamber within the beamline which measures the dose. The accelerator is then calibrated to give a particular absorbed dose under certain conditions, with the specifics varying between centres [45].

In order to contextualise the theory within this chapter, a brief description of the NPL proton calorimeter is required, which is further expanded in section 3.4. The calorimeter consists of a small graphite disk surrounded by multiple graphite jackets, separated by vacuum gaps. The core and jackets are embedded with thermistors to measure the temperature in each component, and the wires from these thermistors connect to a printed circuit board located outside the first graphite jacket.

3.1 Purpose of Radiation Dosimetry

In any cancer treatment the aim is to maximise the dose given to the tumour (to give the highest probability of killing the cancerous cells and avoiding recurrence),
while minimising the dose to the surrounding tissue (to avoid side effects and the risk of causing secondary cancers). In order to provide the optimum treatment using radiotherapy, the exact amount of energy being delivered to any given volume within a patient (the dose) needs to be known, which requires both accurate targeting and knowledge of the beam output. This is why accurate dosimetry is vitally important.

The requirement on the uncertainty in the energy transferred (and therefore the dose delivered) to a target volume is that the standard uncertainty should be less than 5% \[46\]. Since other contributions to the uncertainty are so high (for example patient positioning, target movement etc.), achieving this uncertainty level requires the absorbed dose to be known with an uncertainty of 1% or less.

In order to coordinate accurate measurement and provide traceability and consistency (not only in radiation dosimetry but across all fields) primary standards laboratories at National Measurement Institutes (NMI) exist in over one hundred countries (though only thirteen of these have primary standard dosimetry laboratories \[47\]). These hold the standards for all fundamental units and develop new standards to provide novel measurement solutions \[48\]. The National Physical Laboratory (NPL) is the UK’s National Measurement Institute, and with new proton centres under construction in the UK \[49\] it is important that NPL is ready to provide measurement services for these centres.

Currently NPL maintains the primary standards for photon and electron reference dosimetry\[1\] for the UK, and disseminates the quantity of absorbed dose by providing calibration certificates for detectors to enable users to calculate the absolute dose from the measured dose, and by carrying out audits on hospitals around the UK. The calibration provides a measurement traceability link to standards in order to ensure national consistency\[2\]. NPL has also worked on the development and improvement of primary standards for photon beams for over two decades \[50\].

Photon radiotherapy has been in widespread use for much longer than proton radiotherapy and as a result a large body of knowledge exists regarding photon dosimetry.

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1Reference dosimetry is dosimetry carried out under reference conditions \[41\].

2International consistency is maintained through the BIPM (International Bureau of Weights and Measures), who coordinate comparisons between national primary standards to ensure agreement within known uncertainties.
Much of the work into proton dosimetry is based on, and utilises, research previously done for photons, however there are some distinct problems that arise only in proton dosimetry. Firstly the knowledge of stopping powers and other interaction quantities (such as scattering powers and nuclear interaction cross sections) are not as well known for protons as for photons; secondly the ionisation density is much higher along the proton track than the photon track; and thirdly nonelastic nuclear interactions need to be accounted for in proton radiotherapy but not in photon radiotherapy (with the exception of photo-nuclear interactions which produce neutrons).

3.2 Absorbed Dose

The absorbed dose is the amount of energy deposited in a material by ionising radiation per unit target mass \[51\]. In radiotherapy the “material” is the tissue that is being irradiated, but to ensure standardisation, clinical reference dosimetry is based on absorbed dose to water, measuring the energy deposited in water rather than tissue. It is possible to convert dose from one material to another \[52\] so if necessary the dose to water can then be converted to the tissue of interest by multiplying by the electron density (for photon therapy) or proton stopping power (for proton therapy). Thus the principal dosimetric quantity of interest is the absorbed dose to water, which is strongly dependent on the absorbing material, but independent of radiation type. It is defined as the energy deposited per unit mass, and is measured in gray \(\text{Gy}\) where \(1 \text{ Gy} = 1 \text{ J/kg}\).

The main method used for primary absorbed dose standards\[2\] is calorimetry, although ionisation chambers, Faraday cups and ferrous sulphate (Fricke) solutions have also been used \[50\]. None of these methods directly provides the dose to water - each provides a reading which must then by converted to absorbed dose to water by multiplying by calibration coefficients and conversion factors. However, calorimetry has an advantage...

\[1\]The gray is an SI derived unit with a restricted usage name (i.e. it can only be used for ionising radiation).

\[2\]Primary absorbed dose standards are “instruments of the highest metrological quality that permit the determination of the unit of absorbed dose to water from its definition and the accuracy of which have been verified by comparison with the comparable standards of other institutions at the same level” \[41\].
advantage over the other methods since calibration does not rely on a characterised reference field. It is also the only fundamental method of measuring the absorbed dose according to its definition, so it is the recommended primary standard dosimetry method for proton beams (and other ionising radiation) \[51\]. NPL uses calorimeters for its absorbed dose standards but other National Measurement Institutes use the alternative methods listed above, which provides robustness to the calibration system.

In a typical beam, the dose can be estimated by multiplying the fluence (the number of protons passing through an area, A, perpendicular to the beam) by the stopping power (the rate at which a proton loses kinetic energy) \[51\]. However, this is only an estimate as the energy lost by the protons is not equal to the energy deposited in the target region since the proton energy may be transferred to neutral secondaries with longer ranges, or converted to rest mass energy via nuclear interactions. Calorimetry inherently provides a method to measure the energy deposition rather than the energy lost by the protons.

3.3 Calorimetry

Calorimetry measures the temperature rise resulting from irradiation in an absorber - assuming all the energy deposited in a material appears as heat (i.e. there is no change in physical or chemical state of the absorber and all the ionisations eventually dissipate to heat) \[51\]. If the specific heat capacity of the absorber is known then the energy deposited can be measured using the following equation:

\[
\Delta E = mc\Delta T
\]  

(3.1)

where \(\Delta E\) is the increase in energy, \(m\) is the mass of the absorber, \(c\) is the specific heat capacity of the absorber and \(\Delta T\) is the radiation-induced temperature increase \[53\]. Using the relationship between energy and dose, the absorbed dose to water, \(D_w\), measured using a calorimeter is given by\[51\]

\[
D_w = c_x\Delta T f_{w,x}
\]  

(3.2)

where \(c_x\) is the specific heat capacity of the calorimeter material \((x)\) and \(f_{w,x}\) is the dose conversion factor of the calorimeter material to water. To put this into context,
for a typical radiotherapy fraction dose of 2 Gy to water, this leads to a temperature rise of approximately 0.5 mK. To obtain an uncertainty lower than 1%, this requires the dose to be measured with an uncertainty of 5 µK. Measurements at room temperature at this level are technically very challenging [52].

Under idealised conditions, a measurement of the temperature rise due to irradiation would result in a step function type graph, with a constant temperature ($T_0$) before irradiation, an infinitely steep increase in temperature ($\Delta T$) due to irradiation, then a higher constant temperature after irradiation ($T_0 + \Delta T$). In practice a graph similar to that seen in figure 3.1 is produced, with the increase in temperature occurring over a finite length of time, and the temperature decreasing after irradiation as energy escapes outside of the measurement region.

![Figure 3.1](image)

Figure 3.1: A typical graph resulting from irradiation of the calorimeter, split into three sections: 1 - no change of temperature in the pre-irradiation section before the calorimeter is irradiated; 2 - a rise in temperature during irradiation due to energy deposition being dissipated as heat; 3 - a decreasing temperature after irradiation as heat is transferred to the surroundings, and the absorber tends back to thermal equilibrium.

The rise in temperature (and therefore the absorbed dose when multiplied by the
specific heat capacity and dose conversion factor $f_{w,x}$ can be found by extrapolating the pre-irradiation section forward and the post-irradiation section back to the midpoint of the irradiation. In this work, the interest is less focused on the temperature rise during irradiation and more focused on the changes in temperature after irradiation.

### 3.3.1 Comparison of Water and Graphite Calorimetry

The materials most widely used for absorbed dose-to-water calorimetry are water [54] and graphite (although work has been done with a calorimeter made from tissue-equivalent plastics [55], as well as polystyrene, aluminium, silicon and other materials in industrial dosimetry [56]). Water has several advantages as a material for absorbed dose calorimetry, the most apparent of which is that using water eliminates the need for a dose conversion factor of the calorimeter material to water (i.e. $f_{w,w} = 1$ by definition). It has well known physical properties and can be made to a very high purity. In addition its low thermal diffusivity means the temperature distribution caused by radiation remains in place long enough to enable measurement of temperature at a point (see table 3.1).

However, practically, there are several drawbacks in comparison with using graphite. The presence of non-water materials used to contain the water need to be avoided, as they can lead to absorption and scattering of the radiation, whereas a graphite calorimeter can be made almost entirely of graphite. The specific heat capacity of water is higher than graphite, meaning the temperature rise in water is approximately six times less than the temperature rise in graphite for the same dose (see table 3.1). The uncertainty on some correction factors are larger than for graphite, especially the chemical heat defect correction [50]. Heat transfer through convection currents within the water need to be accounted for (in addition to heat transfer through conduction) [57], although graphite requires radiative heat transfer corrections. Contamination is a bigger problem for water calorimetry. Finally the low thermal diffusivity can also be a disadvantage since once the water calorimeter has been irradiated it can take hours to settle back to its initial conditions, meaning the number of irradiations possible per day is lower in water phantoms than in graphite phantoms.

Despite graphite calorimeters requiring a conversion factor for dose-to-graphite to
Table 3.1: Isobaric mass heat capacity \[58\] and thermal diffusivity of water \[50\] and graphite \[59\], at 20\(^\circ\)C. The lower specific heat capacity of graphite compared to water means graphite calorimeters have a higher sensitivity.

<table>
<thead>
<tr>
<th></th>
<th>Specific Heat Capacity (Jg(^{-1})K(^{-1}))</th>
<th>Thermal Diffusivity (m(^2)/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>4.180</td>
<td>1.43 x 10(^{-7})</td>
</tr>
<tr>
<td>Graphite</td>
<td>0.710</td>
<td>0.80 x 10(^{-4})</td>
</tr>
</tbody>
</table>

dose-to-water, over the range of proton energies used in clinical therapy, graphite very closely matches the scattering properties of water, and the ratio of stopping power in water and graphite is approximately constant so the shape of the dose distribution will be almost the same in water as in graphite (for electromagnetic interactions). For nuclear interactions, the non-elastic nuclear interaction ratio has a large energy dependence, especially at energies less than 100 MeV; although since the contribution of nuclear interactions to the total dose is small, these differences have only a small impact \[60\]. In addition graphite calorimeters have the advantage over water calorimeters of being able to be run in isothermal mode which greatly increases the number of irradiations possible per day.

Despite their differences, both types of calorimeter will continue to be developed and used at PSDLs as the different approaches provide robustness to the calibration system \[61\].

### 3.3.2 Calorimetry in Scanned Beams

In a typical broad beam, the whole of the absorber of interest is within the beam and there is a constant dose across it. However, if the absorbed dose (and therefore temperature) distribution is non-uniform, this leads to heat transfers and net heat loss or gain in components, affecting the accuracy of the measurements. In scanned proton beams, the method of delivery and size of proton beams frequently means that only part of the absorber is in the beam at any one time, and the flow of heat is over similar time scales to the response of the calorimeter itself. This can lead to larger uncertainties in dose measurements unless the response of the calorimeter is fully understood. A similar issue occurs in low-energy ocular proton beams, which have a short range and
limited beam width, hence it was useful to carry out experiments in both beams.

It is important to develop and characterise a calorimeter for scanned beam proton therapy since therapy centres offering the PBS modality are becoming more prevalent, and understanding the calorimeter response will lead to more accurate dosimetry.

### 3.3.3 Correction and Conversion Factors

The most important conversion factors in graphite (or other non-water materials) calorimetry are the water-to-graphite stopping power ratio and the fluence correction factor, since these convert dose-to-graphite to dose-to-water. In addition a multitude of correction factors and uncertainties are introduced to account for (among others): the physicochemical heat defect; heat transfer by radiation across the vacuum gaps and conduction through the thermistor wires; non-uniformity in the radiation field; a correction for the presence of vacuum gaps; volume averaging effects over the core and impurities of the thermistors.

The water-to-graphite stopping power ratio is the main factor of uncertainty, estimated as 1% at the $k = 1$ level[^1] for photons by Seuntjens and Duane [50]. The correction factors for converting absorbed-dose-to-graphite to absorbed-dose-to-water arise since the charged particle spectra in water and graphite may differ at the same depth due to the differences in secondary particles produced and in the absorption of protons in non-elastic nuclear interactions. Both can be modelled using Monte Carlo simulations. The two effects tend to act in opposing directions, leading to relatively small dose conversion corrections of around 0.3% for low energy beams and 1% for high energy beams, although the correction is also depth dependent, such that the correction needed is lower at shallower depths [41].

Another important correction factor is the physicochemical heat defect, which quantifies the difference between the energy absorbed from ionising radiation and the energy appearing as heat, arising from physical or chemical changes to the absorber material [50]. Physical changes include a change of state (this is avoided by using absorber materials far from their phase transition temperatures), or displacement of atoms from

[^1]: $k$ is the coverage factor, which 'scales' the combined standard uncertainty (equivalent to one standard deviation). For a normal distribution $k = 1$ gives a confidence level of approximately 68%. 

their positions within a lattice (creation or annihilation of lattice defects). Chemical changes are more complicated for water calorimeters [62] but are less of a problem for pure graphite calorimeters, with the exception of dissolved oxygen, discussed below.

There is an exothermic chemical heat defect in graphite calorimeters due to the reaction of the medium with dissolved oxygen - this causes an initial over-responsiveness of around 2% but it disappears (due to oxygen depletion) after sufficient pre-irradiation [11]. If pre-irradiation has occurred and the calorimeter is kept under vacuum then the chemical effect is assumed to vanish [11]. Physical heat defects due to the creation and annihilation of interstitial lattice defects have been measured to be below 1% for low energy protons [63]. Chemical heat defects in the thermistor and glass bead have not been quantified but are assumed to have a negligible effect due to their small size in relation to the calorimeter. Overall, a relative standard uncertainty of 0.1% at the $k = 1$ level is applied for the physicochemical heat defect [11].

Heat transport must also be considered for graphite calorimeters in proton beams since the thermal diffusivity (the ability to conduct heat relative to the ability to store heat) of graphite is relatively high in comparison with water. This leads to heat flow away or towards a measurement point from the irradiated surroundings and any temperature gradients in a sample of graphite have typically been redistributed to give a homogeneous distribution well within the irradiation time. The different components of the calorimeter (core, inner jacket and outer jacket) are separated by vacuum gaps, which limit heat loss to the environment via conduction and convection, but there is radiative heat transfer across the vacuum gaps and heat conduction along the thermistors (an example of the observer effect, where the act of measuring a quantity changes the value of the quantity itself [64]). The heat conduction along the thermistors is minimised by using the longest and thinnest wire that are practically possible. In addition, the thermal properties of the thermistors and PCB are different to that of graphite, so may rise in temperature more or less than the surrounding material, affecting the heat conduction.

In the Bragg peak region, the absorbed dose gradient is steep, which can lead to steep temperature gradients, leading to heat flow away or towards the measurement point. This was partly avoided in the Clatterbridge measurements by using a SOBP,
so only minor corrections are required \cite{65}; however, the distal edge is only at approximately 3 cm depth so would still be close to the measurement point. However, in the scanned beam at Prague, lateral dose gradients are steep, and although the time in which a layer is painted is short in comparison with the thermal time constants in graphite, the time between adjacent layers is of the same order of magnitude, meaning considerable heat conduction can occur \cite{66}.

There are correction factors associated with the radiation field itself, for example the profile uniformity correction factor, which takes account of the fact that the radiation field profile may not be flat and thus the dose at the thermistor probe (the measurement point) may not be the same as the dose at the centre of the core (the reference point) \cite{50}.

If all these corrections can be accurately quantified then the true temperature rise due to the radiation (and thus the average dose) can be calculated if the mass of each component is known.

### 3.4 Graphite Calorimetry at NPL

Many laboratories around the world \cite{52} use a graphite calorimeter for photon beams based on the design of Domen and Lamperti \cite{67, 68}, with multiple components separated by a vacuum system to minimise heat loss to the surroundings. However, graphite calorimetry has never previously been used as a primary standard dosimetry method for clinical proton beams, despite having been performed and recommended for many years \cite{69}. For this reason staff in the Radiation Dosimetry department at NPL developed a graphite calorimeter for proton dosimetry - similar in structure to an electron/photon graphite calorimeter (see figure 3.2). It is the only graphite calorimeter in the world that is being developed for proton beams (water calorimeters for proton beams are under development at standards laboratories in the Netherlands, Switzerland, Canada and Germany) \cite{41}.

Note that the calorimeter characterised in this thesis is not the same as that referred to in literature as the “small portable graphite calorimeter” \cite{69} (which in turn discriminates it from a previous “portable graphite calorimeter” which was larger in size and octagonal in shape \cite{70}).
3.4. Graphite Calorimetry at NPL

Figure 3.2: the NPL electron/photon (left) and proton (right) graphite calorimeters held in their metal frames

3.4.1 Measuring the Energy Deposition

The temperatures of the graphite components within the calorimeter can be measured very precisely (to ±0.0001 K), using thermistors (resistors with a strong temperature dependence) connected to Wheatstone bridges, and from this the dose can be calculated by measuring the electrical output [71]. The bridge out-of-balance voltage is converted to temperature using a cubic formula derived from the thermistor calibration data. Note that since the temperature rise (as opposed to the absolute temperature) is the quantity of interest, the thermistors are calibrated relative to reference temperature standards [50].

The thermistors in the calorimeter were individually calibrated so their resistance dependence on temperature was known. In the jackets thermistors were grouped into networks of those with a similar response and recalibrated after being connected to the Wheatstone bridge and nanovoltmeter. Thus the temperature rise can be calculated
from the change bridge out-of-balance voltage. It is possible to calibrate the system at any time by using the heating thermistors to dissipate a known amount of electrical energy within the core, and using the sensing thermistors to measure the rise in temperature.

There are four common modes of operation in which the NPL proton calorimeter can be run: isothermal, full-adiabatic, quasi-adiabatic and non-adiabatic. In the isothermal mode, the temperature of all the components is kept constant; electrical energy is supplied to heat the components and keep them at a chosen temperature (which is higher than room temperature). During irradiation, the beam will heat the components, so the electrical energy supplied drops to maintain a constant temperature. If the temperature is kept at a constant level, then the drop in electrical energy supplied will be equal to the radiation energy supplied to the calorimeter.

In the full-adiabatic mode, the temperature in all components is allowed to drift, so any energy deposited in the calorimeter by the radiation presents as a rise in the temperature of the components. In this mode there is no electrical heating involved (or, more accurately, the components are set to run in constant power mode with a setting of zero Watts), only measuring of temperatures using the sensing thermistors.

In the quasi-adiabatic mode, the temperature of the outer jacket is fixed, but that of the core and inner jacket are allowed to drift - this mode of operation is sometimes used instead of the full adiabatic mode because the room temperature is not often stable and changes in the room temperature are much larger than those induced during irradiation. This can make it difficult to see the radiation induced temperature rises, so this operating mode provides an environment with greater stability for the inner components. Similarly in the non-adiabatic mode, the outer and inner jackets are set to run at a constant temperature, while the core temperature is allowed to drift. This provides an environment for the core that is even more stable than when operating in quasi-adiabatic mode.

Note that corrections must be applied for the presence of the thermistors within the calorimeter: they have a lower heat capacity than graphite, and different radiation absorption characteristics.

Ideally, steep thermal energy gradients should be avoided in calorimetry, but these
3.4. Graphite Calorimetry at NPL

Gradients are inevitable in scanned proton beams so in order to accurately measure the dose deposited in the calorimeter, isothermal mode is the preferred method of operation. However, in the experiments described in this thesis the aim was to investigate how the temperature changed over time rather than directly measuring the absorbed dose, so the full- and quasi-adiabatic modes of operation were used.

3.4.2 Calorimeter Structure

The calorimeter itself consists of a cylindrical graphite core (nominally 2 mm in height and 16 mm in diameter), surrounded by a graphite inner jacket, a graphite outer jacket and a graphite mantle arranged in a nested construction (see figures 3.3 and 3.4). These graphite structures are in weak thermal contact; they are held apart by expanded polystyrene supports, and the air between them is evacuated to create a vacuum.

![Figure 3.3: CAD cross-sectional image of the NPL proton graphite calorimeter](image)

When using the graphite calorimeter in a “small” beam (of diameter less than 10 mm) only a small proportion of the core and graphite jackets will be irradiated which can cause substantial heat flows to surrounding volumes, affecting the temperature drifts measured by the thermistors [60]. This thesis contains details of the first measurements carried out in this kind of small beam, and analyses the resulting heat flows.

The core is embedded with four thermistors - two for sensing temperature and two
3.4. Graphite Calorimetry at NPL

Figure 3.4: Schematic diagram of the NPL proton graphite calorimeter, showing the different components. This diagram would be rotated 360° around the blue line to give the full calorimeter. (The printed circuit board (PCB) is excluded from this diagram.)

...for heating (used when the calorimeter is operating in isothermal mode) embedded approximately 2 mm deep into the side walls of the core and positioned equidistantly around the circumference. These thermistors are encapsulated in small glass beads, and are connected to platinum leads that have a diameter of 32 µm and a length of 3 mm. This takes the platinum leads out of the core and into the inner jacket where they are welded to 200 µm diameter copper leads [72]. The sensing thermistors are used to measure the temperature in the core and can (when operating in isothermal mode) feedback to a LabVIEW program which controls the power supply units connected to the heating thermistors, which then provide the required energy to increase or decrease the temperature of the core. The thermistors are connected to an annular PCB (printed circuit board) seen in figure 3.6 and then each is connected into a 1.4 V high stability DC bridge composed of three 25 kΩ high precision metal foil resistors, forming a Wheatstone bridge (example shown in figure 3.7), which balances at approximately 22°C. The thermistors are held in place using epoxy glue within holes radially drilled into the sidewalls of the core; as a percentage of the total mass of the core, the
3.4. Graphite Calorimetry at NPL

Figure 3.5: Radiograph of the calorimeter showing the core implanted with thermistors, and details of the PCB wiring

thermistors comprise 0.14% and the epoxy glue 0.39% [73].

The jackets and mantle that surround the core were manufactured in two parts (named “front” and “back” for the jackets, and “lid” and “base” for the mantle) with interlocking ‘keys’ to ensure they do not slide across or rotate against each other. The inner jacket has the following nominal dimensions: 5 mm in height and 23.5 mm in diameter with a cavity 3.5 mm in height and 17.5 mm in diameter in the centre. The nominal dimensions of the outer jacket are complicated by the non-standard shape of the side walls (see figure 3.4): the height is 8 mm, with a 6.5 mm cavity height, while the diameter varies between 31 and 32 mm, with the cavity diameter varying between 25 and 28 mm. The mantle has a height of 12.5 mm and cavity height of 9.5 mm, with an outer diameter of 100 mm, and a variable cavity diameter between 32 and 40 mm. These nominal dimensions were provided for manufacture, and then the height of each component was measured after manufacture, producing the actual measurements shown in table 3.2.
3.4. Graphite Calorimetry at NPL

Figure 3.6: The printed circuit board (PCB) contained within the NPL graphite calorimeter

Table 3.2: Comparison of nominal and measured thickness of each component with $k=1$ uncertainties [74]. Note that thickness here refers to the dimension along the axis parallel to the beam direction, as measured at the centre of each component.

<table>
<thead>
<tr>
<th>Component</th>
<th>Nominal Thickness (mm)</th>
<th>Measured Thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mantle Lid</td>
<td>1.5</td>
<td>1.5567(67)</td>
</tr>
<tr>
<td>Outer Front Jacket</td>
<td>0.75</td>
<td>0.7478(22)</td>
</tr>
<tr>
<td>Inner Front Jacket</td>
<td>0.75</td>
<td>0.8060(39)</td>
</tr>
<tr>
<td>Core</td>
<td>2.0</td>
<td>2.0455(12)</td>
</tr>
<tr>
<td>Inner Back Jacket</td>
<td>0.75</td>
<td>0.7713(38)</td>
</tr>
<tr>
<td>Outer Back Jacket</td>
<td>0.75</td>
<td>0.7534(14)</td>
</tr>
<tr>
<td>Mantle Base</td>
<td>1.5</td>
<td>1.5875(59)</td>
</tr>
</tbody>
</table>

The diameters of each component were not directly measured after manufacture, but the masses of each component were measured, so the diameters could be calculated...
Figure 3.7: A schematic circuit diagram of the DC Wheatstone bridge used in combination with the sensing thermistor networks housed within the calorimeter. The blue circle represents the point of measurement. The resistances $R_2$, $R_3$ and $R_4$ are known, $R_{th+wire}$ is the resistance of the thermistor and wire system, $V_s$ is the supply voltage and $V_{out}$ is the bridge out of balance voltage. Note the leads to the sensing thermistor are actually twisted to reduce the effect of noise.

using the density. However since the structure of the calorimeter was to be simplified for simulations, nominal diameter values were used.

In addition to the two core sensing thermistors (which are independent of one another), there are also four sensing thermistors in each jacket component (front and back), two sensing thermistors in the mantle lid and another pair in the mantle base. These sensing thermistors (in components other than the core) are electrically connected into series and parallel to form a network for each component. Each of these networks are connected to one arm of (separate) Wheatstone bridges, measuring the temperature of each component and determining the temperature rise induced by radiation. Note that the thermal properties of the thermistor bead and surrounding glass are different to that of graphite, and thus corrections must be made for their differing behaviour.

The electrical leads from the PCB are connected via vacuum feed-through connectors and an interface box to a custom made data logging program, which has a sampling rate of 4 Hz (taking data readings 4 times per second). Each data measurement is as-
signed a reading number for easy referencing; there are some graphs in chapter 4 that are plotted in terms of reading numbers instead of time.

To the rear of the mantle base, a thick graphite block is used to provide sufficient backscatter, referred to as the “backing block” in the COMSOL and TOPAS simulations. Furthermore, in order to position the core at a required depth in a beam, graphite build-up plates can be added in front of the calorimeter (as used in the experiments described in chapter 5).

### 3.4.3 Heat Transfers Within The Calorimeter

The heat transfers between components of the calorimeter are intended to occur mainly by radiative heat transfer across the vacuum and partly by conduction along the thermistor leads to the PCB.

**Radiative Heat Transfers**

The radiative transfers for “black bodies” (those which absorb all radiation incident on the surface) are proportional to $T^4$ as given by the Stefan-Boltzmann Law [75]; for “grey bodies” the incident radiation is partially reflected, absorbed or transmitted and the Stefan-Boltzmann Law is modified by the inclusion of the emissivity coefficient:

$$ P = \epsilon \sigma A (T_1^4 - T_2^4) $$

where $P$ is the energy radiated per second (the rate of heat loss), $\epsilon$ is the emissivity, $\sigma$ is the Stefan-Boltzmann constant, $A$ is the surface area of the emitter and $T_1$ and $T_2$ are the temperatures of the components (measured in degrees Kelvin). The emissivity is a property of a material’s surface and shows how effective it is in emitting energy as thermal radiation. It varies between 0 and 1 (for a perfect black body) - for graphite in its natural form the emissivity varies with temperature between 0.70 and 0.80; however, pressed and filed graphite has an emissivity of 0.98, while unoxidised graphite has an emissivity of 0.81 [76].
Conductive Heat Transfers

The conductive heat transfers are described by Fourier’s Law of heat conduction, which states that heat transfers are proportional to the temperature gradient:

\[
\vec{J} = -k \nabla T
\]  

(3.4)

where \( \vec{J} \) is the heat flux (heat energy flowing per second per unit area), \( k \) is the thermal conductivity, \( \nabla \) is the del operator\(^1\) and \( T \) is the temperature.

For time dependent problems, the thermal diffusion equation (or heat equation) is used; a partial differential equation that describes the variation in temperature in a given region over time \([77]\):

\[
\frac{\partial T}{\partial t} - \alpha \nabla^2 T = 0
\]  

(3.5)

where \( T = T(x, y, z, t) \) is the temperature as a function of space and time and \( \alpha \) is the thermal diffusivity. This can be rewritten to include a heat source, and ignoring any viscous heating or pressure work it can be expressed as (for the derivation see \([53]\)):

\[
\rho c_p \frac{\partial T}{\partial t} - \nabla \cdot (k \nabla T) = Q
\]  

(3.6)

where \( \rho \) is the density, \( c_p \) is the specific heat capacity at constant pressure, \( T \) is the absolute temperature, \( k \) is the thermal conductivity and the \( Q \) term contains the heat sources, which in this case are the absorbed dose due to irradiation and the heat radiated from other calorimeter components. This is the heat transfer equation that is solved in the COMSOL simulations (see section 4.2.1).

3.4.4 Specific Heat Capacity

The specific heat capacity (\( c_p \)) of a sample of graphite of similar size and from the same batch as the core was measured using the same method as in Williams \textit{et al.} \([59]\) over a temperature range between 16°C and 28°C \([71]\). This resulted in the following linear fit of the temperature dependence:

\[
c_p^g = 711.46 + 2.74(T - 295.15)
\]  

(3.7)

\(^1\)Such that \( \nabla = \left( \frac{\partial}{\partial x} \vec{i} + \frac{\partial}{\partial y} \vec{j} + \frac{\partial}{\partial z} \vec{k} \right) \) and \( \nabla^2 = \left( \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} \right) \)
where \( c_p \) is the specific heat capacity of graphite, measured in J/kg·K and \( T \) is the temperature, measured in K. The type A uncertainty was 0.03\% and the type B uncertainty was 0.05\% (from the sensor thermistor and electronics calibrations). It was previously found that high dose irradiation (in excess of 3 MGy) did not significantly change the value of the specific heat capacity [59].

### 3.5 COMSOL Multiphysics

COMSOL Multiphysics® is a scientific software package (previously known as Femlab (Finite Element Modelling LABoratory) [78]) which was used to build a model of the calorimeter then track the heat flow through it during and after irradiation. COMSOL is a finite element method simulation software which allows the user to model and simulate any physics based system that can be described by a partial differential equation (PDE). The finite element method is a numerical technique used to find approximate solutions to PDEs by dividing a problem into smaller, simpler parts (called finite elements), for example having simple equations that locally approximate the original PDEs [79]. In the case of heat transfer modelling, the PDE to be solved is the heat equation (given in equation [3.6]). The “Multiphysics” part of the name refers to its ability to solve coupled physical phenomenon simultaneously [80], e.g. radiation and conduction of heat.

Initially, basic 2D simulations were constructed, for example an inner box was taken to be a heat source, surrounded by a vacuum, then another box and the temperature at various points in the outer box was measured. From these simulations an understanding was developed of how the program worked.

Once a more thorough knowledge had been obtained, and the effect of adjusting some of the parameters had been tested, simple 3D geometries with graphite and vacuum regions and cylindrical heat sources were modelled, and the surface-to-surface radiation was implemented.
3.6 Monte Carlo Modelling

Monte Carlo (MC) modelling is a technique that is widely used in radiation transport applications, and was developed by Stanislaw Ulam and others at Los Alamos Laboratory in order to investigate neutron shielding [81]. It uses mathematical algorithms and random numbers to solve complex numerical problems which allow the user to simulate experimental set-ups without the use of valuable beam time, both in terms of cost and efficiency of patient treatment. They can accurately predict, for instance, dose distributions within a treatment volume, and can be used when an experimental set up would not be possible.

It is so named because of the probabilistic nature of the algorithms (which sample from stochastic distributions), modelling the probabilistic nature of the particle interactions. A statistical output is produced, and it is because of this nature that many particles need to be simulated to give an accurate result, using the law of large numbers. Each particle that is simulated has a particle history, encompassing its path, any secondary particles produced and its energy distribution. The greater the number of histories, the smaller the error on any results (the uncertainty being proportional to $1/\sqrt{N}$ where $N$ is the number of histories).

What makes MC calculations applicable to radiation physics is that individual particles, and all their secondary interactions, are tracked from the source to absorption. The particle takes many small steps along its physical path, and in each step the particle may undergo interactions with other particles and the material it is travelling through. The likelihood of a particle interacting with this material is given by the interaction cross section. Classically, the cross section can be thought of as the “target area” of an atom, where if a particle passed through the area it would undergo an elastic interaction with the atom. However, the cross section also encompasses the nuclear cross section which describes the probability of a nonelastic nuclear process occurring, and depends not only on the geometry of the atom but also on the nature of the particle (among other factors).

The elastic interactions for the MC calculations are obtained from the Bethe-Bloch equation and Molière’s theory, while the nuclear cross section, $\sigma$, can be defined for a
Monte Carlo Modelling

3.6. Monte Carlo Modelling

The target nucleus can be represented as:

\[ \sigma = \frac{P}{\Phi} \]  

(3.8)

where \( P \) is the probability of interaction for a target nucleus, and \( \Phi \) is the particle fluence \[^{18}\].

Each particle originates from a user-defined source, and its path is simulated step-by-step through the user-defined geometry. Any interactions (and their outcomes) that a particle will undergo in a given step is randomly chosen on the basis of the probability distributions defined by the interaction cross sections (or alternatively the mean free path of the particles). The particle track is the sum of all the steps. At the end of a step, the new values for the particle’s position and energy are calculated and used as the basis for any interactions in the next step.

Truly random numbers are not required for Monte Carlo simulations, and in particle transport calculations generally pseudo-random numbers are used instead, which are (long) sequences of numbers. A starting seed value is specified which decides the starting position in the sequence, acting as the starting “dice roll” in the “random number” generation. The use of pseudo-random numbers can be useful for reproducibility since if the same starting seed is used, the same result should be obtained (on a specific computer), although care must be taken to vary the starting seed if independent results are to be combined.

In this work Monte Carlo was mainly used for the purpose of beam line simulation, the physics of proton beams, and obtaining calorimeter correction factors.

### 3.6.1 GEANT4

The GEANT4 (GEometry ANd Tracking 4) Simulation Toolkit is a MC particle transport simulation package. It was developed by an international collaboration at CERN and written in the programming language C++ \[^{10}\]. It is used in a wide range of applications (including astrophysics, nuclear physics and high energy physics); part of the reason for its popularity originates in the freely available source code. There are three main parts to a GEANT4 code: a physics list, the primary generator and the detector construct. The physics list specifies which processes can occur during a simulation; the primary generator specifies the initial particle source (e.g. particle type,
3.6. Monte Carlo Modelling

energy, direction); and the detector construct specifies the physical properties of the system (e.g. materials, geometry, scoring regions [82]).

3.6.2 TOPAS

TOPAS (TOol for PArticle Simulation) [8] is a piece of software that acts as a less complex and more user-friendly interface to GEANT-4, and was designed for proton beams. It preselects the physics list (based on those appropriate for proton therapy), some aspects of the primary generator (although these can be manually changed) and contains pre-built geometry components (e.g. range modulator wheels) allowing the user to concentrate on the detector construct.

It was developed by Joseph Perl et al. at Massachusetts General Hospital, and was first used for work in this thesis when it was in the beta-testing phase (the last phase of software testing before release), although later simulations were executed using version 1.2. TOPAS has been verified against measurements from Massachusetts General Hospital (among others).

Using TOPAS it is possible to construct an accurate beam line geometry, which can be visualised using OpenGL, then run multiple simulations with millions of histories. The data are output in csv format, which was then imported into Excel for analysis.

The physics list is composed of different modules, each of which defines different types of physical interactions that particles can undergo within a material, e.g. there are modules covering nuclear decay and electromagnetic interactions. The default physics list in TOPAS is:

```
sv:Ph/Default/Modules = 6 "g4em-standard_opt3" "g4h-phy_QGSP_BIC_HP"
"g4decay" "g4ion-binarycascade" "g4h-elastic_HP" "g4q-stopping"
```

which correspond to these GEANT4 classes:

- G4EMStandardPhysics_option3
- HadronPhysicsQGSP_BIC_HP
- G4DecayPhysics
- G4IonBinaryCascadePhysics
• G4HadronElasticPhysicsHP

• G4QPhotoNuclearPhysics

The first class covers electromagnetic interactions, while the latter ones cover various nuclear effects. This default physics list was used in all the TOPAS simulations apart from those in section 6.1.1 where only the first class was included.

A significant difference from GEANT4 in terms of geometry is the inclusion of three main dividable components; “TsBox”, “TsCylinder” and “TsSphere”, which can be defined not only by their shape and size but also divided into bins. Binning is the term for dividing a shape into compartments, or bins, such that the quantity of interest (in this case, the dose) can be calculated (or scored) in each bin. By creating these dividable components, the process of scoring can be greatly simplified, and it offers the user more flexibility.
Chapter 4

Static Proton Beams

This chapter describes the calorimeter measurements with the corresponding COMSOL and TOPAS modelling, for static pencil proton beams. In this context static beams are those where the calorimeter and beam are stationary with respect to one another, as opposed to the work in Chapter 5 where the calorimeter is moving relative to the beam, or the beam itself is scanning.

While the main objective of this thesis research project is to understand the response of the calorimeter in scanned beams, characterising the response in small static beams is also valuable since scanned beams can be considered as a superposition of single beam spots. Thus by performing an analytical study of single static proton beams, a greater understanding of scanned proton beams can be achieved.

4.1 Calorimeter Measurements

4.1.1 Set Up and Methodology

At Clatterbridge the graphite calorimeter (in full adiabatic mode) was irradiated with a collimated beam using a brass collimator with a 4 mm diameter circular hole. The 4 mm collimator was chosen both to provide a beam small enough to irradiate only part of the calorimeter and to be similar in size to the beams in spot scanning systems. However, the small beam size increased scattering from the collimator (relative to the
4.1. Calorimeter Measurements

number of primary protons in the field\[1\], as well as decreasing the signal from the calorimeter since the total energy deposited was lower. A spinning perspex (PMMA) modulator wheel (rotating at a rate of 30 Hz or 1800 rpm \[34\]) was used to produce a fully modulated proton beam (wheel reference number 769).

Figure 4.1: Side view of the Clatterbridge set up. The brass nozzle can be seen extending from the beamline (silver box) on the left hand side of the picture. In the middle is the calorimeter in its frame.

The calorimeter was mounted on a carriage which could be moved perpendicular to the beam direction by a user-specified distance and could also be “jogged” continuously (i.e. repeatedly moved a short user-specified distance of 1 mm, resting at each position for approximately 1 second) to give a simple approximation to a scanned beam.

The carriage was then placed on a table connected to the treatment chair which could be moved along the beam direction if needed. In the measurements described in the current work it was in a fixed position, with the front face of the calorimeter approximately 20 cm from the collimator. Ideally the calorimeter would have been positioned closer since the isocentre is 7 cm from the collimator nozzle, and distances greater than this suffer from a degraded lateral beam spread, but the calorimeter frame

\[1\] In addition, most of the protons scattered from the edges of the collimator are only scattered by a small angle, so in a smaller field there are more scattered protons in the centre of the field.
restricted this possibility.

Figure 4.2: Similar photo to figure 4.1 with the beamline on the left hand side, showing the calorimeter mounted on the patient chair (right hand side of image, metal frame).

Figure 4.3: Showing the calorimeter on the wedge with the positioning plate in place.

The frame of the calorimeter was placed on a Styrofoam wedge which held the calorimeter at a $45^\circ$ angle. This was required so that when the proton beam was
4.1. Calorimeter Measurements

Figure 4.4: The (blue) polystyrene wedge which held the calorimeter at a 45° angle.

offset from the central axis, the beam would not directly irradiate the thermistors (see figure 4.5), reducing the effect of thermistor irradiation that occurs under normal operation.

A mirror was used to check that the front face of the calorimeter was perpendicular to the beam. The alignment plate and film (seen in figure 4.6) were used to check the beam was centred on the calorimeter. The analysed film was later used to refine the COMSOL model by giving an indication of the lateral beam spread (figure 4.7 as well as Appendix A, section A.1).

Before measurements began, an X-Y diode scanner was used to check the flatness of the beam profile which can be affected by the upstream steering magnets. After the flatness measurements were complete, a parallel plate monitor chamber was mounted on the collimator arm to measure the beam current. The current was measured using a PTW Unidos webline (on medium range, 28 nA with +400 V).

The hospital system is set up to give an output in monitor units (MU), and could deliver a maximum of 100 MU/minute, corresponding to a maximum dose rate output of ∼ 45 Gy/minute and a beam current of ∼ 1.4 nA. Different combinations of dose rate and total MU delivered were tested. Figure 4.8 shows an example of the average
4.1. Calorimeter Measurements

Figure 4.5: Radiograph of the calorimeter core through the front face of the mantle. Irradiations were made along the line running at 45° to the perpendicular, to avoid irradiations of the thermistors (the black dots around the outside).

Figure 4.6: Films irradiated in the proton beam at CCC. The film was taped to the front face of the calorimeter at a distance of approximately 20 cm from collimator. The film on the left was done at the start of the first day of measurements, while the film on the right was taken at the start of the second day of measurements to ensure the set-up remained the same.
4.1. Calorimeter Measurements

Figure 4.7: The films in figure 4.6 were scanned using an Epson 10000XL scanner, and analysed using ImageJ [83] to produce these dose curves. The figure shows the small day-to-day variation in the beam produced by the accelerator.

of results (and their corresponding standard deviations) with the following settings:

- 50 MU at 100 MU/minute (approximately 30 seconds for delivery)
- 25 MU at 60 MU/minute (approximately 25 seconds for delivery)

The curve in which 50 MU was delivered reaches a higher peak temperature than the one where only 25 MU was delivered, since more dose and therefore more energy has been deposited in the core. The graphs have been plotted such that both irradiations finish at 40 seconds, but because of the different dose rates, the gradients of the irradiation sections are different.

It might be expected that doubling the dose delivered should double the temperature rise observed in the calorimeter, but it is not intuitively obvious that the post irradiation temperature drifts would be similar in this case, especially if the dose rates were different in each case. There may have been difficulties in combining the results of graphs with different dose rates - heat flows within the calorimeter cause cooling to occur in the core even during irradiation; the lower the dose rate, the longer the time taken to deliver the dose, so more cooling occurs and the maximum temperature reached is lower, causing
4.1. Calorimeter Measurements

Figure 4.8: The average of two sets of irradiations carried out at different dose rates and different total dose delivered (from Clatterbridge data, text files 2, 5 & 30, Core 1 thermistor)

the post-irradiation gradients to differ. However, multiplying the 25 MU data by two (to give an effective 50 MU dose) and plotting the result against the 50 MU data, shows there is very little difference in the post-irradiations sections (see figure 4.9). This shows that there is a linear heat transfer as a function of temperature between the core and the inner jacket.

The higher dose rates provided a better signal-to-noise ratio but were higher than would be normally used for treatments and as a result the cyclotron system sometimes struggled to maintain these dose rates and would cut out. Where possible, the higher dose irradiations were used for analysis, but the lower dose irradiations were included and combined in the analysis if necessary, for example where there are few unbroken high dose irradiations.

4.1.2 Measurements Taken

As described in Section 2.3 irradiations were carried out with the beam both centred on the core (0 mm offset) and horizontally offset from the core. Measurements were taken at the following beam offsets: 0, 3, 7, 9, 11, 13, 15, 18, 23, 28, 33, 41 (all in
4.1. Calorimeter Measurements

Figure 4.9: All the individual irradiations contributing to figure 4.8 with the 25 MU dose irradiations multiplied by two. The range in start times results from the different lengths of time for dose delivery (from Clatterbridge data, text files 2, 5 & 30, Core 1 thermistor)

mm). The offset was set using the carriage controls, then the beam was switched on, the irradiation ran for approximately 30 seconds (depending on the beam output), and then it was left to cool for approximately 2 minutes so the temperature of the calorimeter components were in a steady state before the next irradiation.

The air temperature and pressure were variable but fluctuated around 22 degrees centigrade, 1010 mBar. The irradiations were repeated at least three times at each measurement point.

4.1.3 Analysis

The Wheatstone bridge voltage data obtained from the Clatterbridge measurements was saved in the form of ASCII files, to be monitored ‘off-line’; a new file was manually created at the beginning of a new set of measurements (in addition a new file is created automatically after one hour of data collection so as to limit the size of the files), so each ASCII file corresponded to a different time period, numbered 1-31. These files are referred to below by their number for easy referencing, and any file may contain a
4.1. Calorimeter Measurements

number of irradiations. The files were imported to Excel for further manipulation and analysis. The temperature in each part of the calorimeter (core 1, core 2, inner front jacket, inner back jacket, outer front jacket, outer back jacket) was calculated using the voltages measured from the Wheatstone bridges using the bridge-voltage ($V_b$) to temperature ($T$) conversion function:

$$T(V_b) = \alpha V_b^3 + \beta V_b^2 + \gamma V_b + \delta \quad (4.1)$$

The values of $\alpha$, $\beta$, $\gamma$ and $\delta$ were obtained from calibration of the thermistors (a method similar to that given in NPL Report 40 [59] was used), table 4.1 displays the values for the Core 1, Inner Front Jacket and Outer Front Jacket thermistors.

Table 4.1: Table of coefficients used in the bridge-voltage to temperature conversion function, to calculate the temperature from the bridge-out-of-balance reading [73]. Values given to 6 s.f.

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>C1 Value</th>
<th>IF Value</th>
<th>OF Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>57.0899</td>
<td>53.9256</td>
<td>57.0123</td>
</tr>
<tr>
<td>$\beta$</td>
<td>15.1970</td>
<td>15.9867</td>
<td>15.4574</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>68.6117</td>
<td>70.2495</td>
<td>69.4551</td>
</tr>
<tr>
<td>$\delta$</td>
<td>21.3749</td>
<td>23.8038</td>
<td>21.6706</td>
</tr>
</tbody>
</table>

The magnitude of the rises in temperature caused by the irradiations meant the temperature drifts over the course of each day were much larger than the temperature increases from irradiation (a representative example is a drift of 150 mK in room temperature over an hour compared to increases of 2 mK due to an irradiation). There were additional problems with electronic noise, especially when the beam position was far from the measurement position (for example when the beam was irradiating only the outer jacket, the temperature increase seen in the core was minimal).

Each time period was split up into individual irradiation periods by cross referencing the time associated with each data point with the time written down manually in the lab book when the beam was switch on. Each irradiation period consisted of a temperature over a length of time prior to the irradiation (pre-irradiation), during the irradiation, and after the irradiation (post-irradiation) which gave a graph similar to that shown
in figure 4.10 from the 2\textsuperscript{nd} irradiation period in the 5\textsuperscript{th} time period, showing the temperatures in the core 1 thermistor.

Figure 4.10: Raw data resulting from an irradiation at 0 mm offset. The temperature of the core 1 thermistor is decreasing due to the cooler relative temperature in the room and surrounding jackets and the irradiation (occurring around reading number 65600) results in a small warming in comparison. Each data point is linked to the next with a straight line, and an enlarged section in the top right shows the data points marked with a cross.

The uncertainties are discussed in detail in section 4.1.4, but the consistency in the individual data points shows the Type A uncertainty is low.

The pre-irradiation section of the curve was fitted with a quadratic functional formula (see figure 4.11) with a large number of significant figures for the coefficients to avoid truncation errors. The range of this fit had a big impact on the resulting curve (see section 4.1.4), so all the fitting was standardised by fitting a length of time prior to irradiation that was equal to the length during and after irradiation (so the fitting length was equal to the irradiation time plus 100 seconds). Extrapolating the fitted curve produces uncertainties which increase as the distance from extrapolation increases, and this can be seen in the final graphs where the standard deviation increases as time after irradiation increases.
4.1. Calorimeter Measurements

Figure 4.11: The pre-irradiation section from figure 4.10 has been extracted and fitted with a quadratic function (plotted in black, with corresponding equation). Graphically the fit was extended 500 reading numbers to check for unexpected behaviour.

This fit was then analytically subtracted from the data (pre-, during and post-irradiation) to eliminate the overall temperature drift, and leave the temperature change due to the irradiation alone. An example of the result is seen in figure 4.12 showing an increase in temperature during irradiation, and a steady drop in temperature post-irradiation.

This procedure was carried out for every irradiation and the resulting graphs were then grouped according to the beam offset and calorimeter component in which they were measured. Since the post-irradiation drift is the quantity of interest, the long section prior to irradiation was eliminated in plotting, and a standardised length of 100 second post-irradiation was chosen. Due to the variability in irradiation timing lengths, all plots were adjusted such that the end point of the irradiation occurred at 40 seconds. Figure 4.13 shows an example of this, grouping all the measurements at 11 mm offset in the inner front jacket thermistor in the 30\textsuperscript{th} period.

Initially analysis was done for every thermistor or thermistor network:

- core 1 (C1)
4.1. Calorimeter Measurements

Figure 4.12: The quadratic function found from figure 4.11 was subtracted from the data and the resulting graph plotted, showing the effect of the irradiation on the temperature in the core without the background temperature drifts.

Figure 4.13: The temperature variation with time for 11 mm beam offset, as measured in the inner jacket. The end point of all the irradiations were set as 40 seconds to allow comparison between irradiations at different dose rates.
4.1. Calorimeter Measurements

- core 2 (C2)
- inner front jacket (IFJ)
- inner back jacket (IBJ)
- outer front jacket (OFJ)
- outer back jacket (OBJ)
- mantle base (MB)

It was expected that the thermistors in the same component should give the same output, within the thermistor calibration uncertainties. On comparison of the results, it was noted that while some pairs of thermistors gave near-identical results, for example the core 1 and core 2 thermistors (as seen in figure 4.14 when the beam was irradiating the centre of the core), in others, such as the inner and outer jacket thermistor networks, there was a larger difference.

![Figure 4.14: Comparison of the results from C1 and C2 thermistors (the different curves are hard to distinguish but they are distinct).](image)

For the inner front and inner back jacket thermistor networks, there was some difference in the peak temperature reached (of the order of 0.05 mK, with the inner
4.1. Calorimeter Measurements

front jacket thermistor network increasing in temperature more than the inner back jacket thermistor network, see figure [4.15], though within 60 seconds this difference is minimised.

![Comparison of the results from IFJ and IBJ thermistors.](image)

Figure 4.15: Comparison of the results from IFJ and IBJ thermistors.

There are several possible reasons for this difference: it could be due to the different masses of the front and back jackets (i.e. the back jacket has a slightly larger mass, so if the same amount of energy is deposited in both, the temperature rise in the back jacket would be smaller); it could be due to differences in how the jackets are constructed, such that the back jacket has a larger area in radiative contact with the core than the front jacket; it could be that this difference is within the calibration uncertainties for the thermistors. Whatever the cause of this difference, it occurs because the front and back jackets are not in perfect thermal contact - they are machined separately and sit together but there will be a thermal resistance between the two.

In the outer jackets, the back jacket suffered from a high level of noise (see figure [4.16]), so only the outer front jacket thermistor network was used in the analysis.

The results from the mantle thermistor were poor due to the low amount of energy deposited in this region, so results from the mantle thermistor were not used.

As a consequence of the similarities between thermistor results, it was decided that only the core 1 (C1), inner front jacket (IFJ) and outer front jacket (OFJ) would be
analysed for the bulk of the measurements, with periodic checks that the similarity held under differing measurement conditions. These thermistors and thermistor networks will now be referred to as the core (C), inner jacket (IJ) and outer jacket (OJ) thermistors.

There were some problems in grouping the graphs since even when the measurements occurred under the same conditions, the dose rate was slightly different for each irradiation leading to graphs like that seen in figure 4.17. However, similarly to figure 4.9, the dose rate differences in the measurements were noted not to have a significant impact on the maximum temperature reached. Thus it was decided to align the graphs from their peak temperature (end of irradiation) as seen in figure 4.18.

4.1.4 Calculating Uncertainties

In the data analysis there are two main contributions to the uncertainty: firstly the reproducibility of the measurements themselves, and secondly the accuracy and reproducibility of the fitting procedure.

The uncertainty on the former can be obtained from the standard deviation on repeated measurements done under the same conditions (see example in figure 4.19). This uncertainty is larger for measurements in the inner and outer jackets since they are
Figure 4.17: These three irradiations were carried out one after another under the same measurement conditions (nominally 25 MU at 60 MU/min), however the dose rate was slightly different each time (from Clatterbridge data, text file 2, irradiations 1, 2 and 3, Core 1 thermistor)

Figure 4.18: The same irradiations seen in figure 4.17 but now aligned by their peak temperature (from Clatterbridge data, text file 2, irradiations 1, 2 and 3, Core 1 thermistor)
more sensitive to fluctuations in room temperature, while the core is better thermally insulated. In addition, since the rise in temperature in the inner and outer jackets are smaller, the signal-to-noise ratio is larger so the fitting to the pre-irradiation section is worse, giving a greater variability in the results.

The uncertainty on the accuracy of fitting is more difficult to capture, but may be estimated from the variability in curves when using different order polynomial functions and different drift times for the fitting.

![Figure 4.19: Average of three irradiations (black line) with one standard deviation either side (light grey lines) (from Clatterbridge data, text file 2, irradiations 1, 2 and 3, Core 1 thermistor)](image)

There was a large variability in the pre-irradiation drift times, ranging from as little as 88 readings (≈ 22 s) up to 1488 readings (≈ 372 s) (since the calorimeter readings are taken 4 times each second). With the short pre-irradiation drift there is a problem with a cubic polynomial over-fitting the curve and producing non-physical results after subtraction in the post-irradiation drift. Where there are long pre-irradiation drifts, quadratic curves may not capture the curvature and there may be obvious deviations (see for example figure 4.20).

Since the fits are being extrapolated, the further the data point lies from the extrapolation (i.e. the start of the irradiation), the larger the uncertainties in the final compar-
4.1. Calorimeter Measurements

Figure 4.20: Example of a poor result after the fit has been subtracted, obtained when using a quadratic fit for an irradiation with a long pre-irradiation drift. (Data taken from the Prague measurements, text file 8, irradiation 1, Core 1 thermistor)

In most cases the measurement was only included when the pre-irradiation time was at least as long as the post-irradiation time, chosen as 100 s, so the pre-irradiation drift needed to consist of at least 400 readings.

The irradiations with a very short pre-irradiation drift (~200 readings or less) could be used but would have very large uncertainties and so were generally discarded if there were other results from similar measurements conditions available.

However, even if a long pre-irradiation drift is available, it may not be prudent to fit it all, for example in figure 4.21 there is a large variability in the final temperature 100 s after irradiation when using different time intervals for the fitting. Although there are 988 readings available pre-irradiation, the curve obtained from fitting 500 readings pre-irradiation best agrees with the other measurements under the same conditions.

Another factor that was found to impact the final curve was the second derivative of the temperature with respect to time, at which the irradiation was carried out i.e. the increasing or decreasing rate of change of temperature. For example, in one session irradiations were carried out at the following offsets: 0, 3, 9, 11, 15 then back to 0 mm (repeating each position 3 times), using the same dose rate and total dose each time.
4.1. Calorimeter Measurements

Figure 4.21: Variability in results occurs when different length of pre-irradiation sections are used for a cubic fit. The numbers in the legend correspond to the length used in the fit (from Clatterbridge data, text file 2, irradiation 1, Core 1 thermistor).

Comparing the six irradiations at 0 mm offset (three at the beginning and three at the end) in figure 4.22, there is a clear split - the first three irradiations agree very well, and there is good agreement for the second set of three, but there is a difference of approximately 0.15 mK between the two sets of final temperatures.

Since the irradiations were carried out under the same conditions this clear split appears strange. The only difference between the two sets is the second derivative of the temperature with respect to time before irradiation. Looking over the full range of temperatures in that session (figure 4.23), the core temperature had a positive second derivative with respect to time before the first set of irradiations (the temperature was increasing at an increasing rate) while before the second set of irradiations, the second derivative of temperature with respect to time was negative (the temperature was increasing at a decreasing rate). This is a product of the fitting method (making the assumption that the drift in background temperature continues in the same manner during and after irradiation as before). Using this information, it can be assumed that if the temperature was changing at a constant rate (i.e. the second derivative with respect to time was zero), the final result would lie between the sets of curves seen in...
4.1. Calorimeter Measurements

Figure 4.22: The first three irradiations (blue) were carried out one after another at the beginning of the session, while the second set of three (red) were carried out at the end of the session (from Clatterbridge data, text file 30, irradiations 1, 2, 3, 16, 17, 18, Core 1 thermistor)

Figure 4.23: The blue ellipse labelled A encircles the first three irradiations at 0 mm offset, while the red ellipse labelled B encircles the irradiations also at 0 mm offset at the end of the session (from Clatterbridge data, text file 30, all irradiations, Core 1 thermistor)
4.1. Calorimeter Measurements

In this particular case, the average of all irradiations would give a good approximation to the result with constant temperature change, but if only one set of irradiations were considered, the final curve would be inaccurate by approximately 0.08 mK, or less than 3% of the peak temperature.

4.1.5 Results

Graphs of the resulting data grouped by offsets are shown in Appendix A. Based on these graphs, it was noted that some offsets were not significantly different from others (for example 0 mm offset and 3 mm offset), while other offsets were too far from the core, producing small signals and large standard deviations, for any meaningful comparison to be drawn (for example 18 mm offset). For the offsets larger than 18 mm (i.e. 23 mm and greater), the signals produced in the calorimeter were too small to be able to distinguish the start and end points of the irradiation. This information is useful from the purposes of determining the largest field size necessary. In addition the data taken at 100 MU/min with 50 MU total dose was the most reliable and had the highest frequency of repeats so it was used for comparison with COMSOL. The subset of measurement offsets used for comparison with COMSOL is as follows:

- 0 mm
- 9 mm
- 15 mm

which are shown below (figures 4.24, 4.25 and 4.26), grouped by the component in which they were measured.

In figure 4.24 the temperature of the core increases the most after irradiation at 0 mm offset (i.e. the beam is centred on the core), then decreases as heat flows out to the other components. Irradiation at 9 mm beam offset causes a smaller increase in temperature, and after the irradiation the temperature is constant, indicating no net heat flow. When the beam is far from the core, as is the case for 15 mm offset, the temperature of the core increases negligibly during irradiation, and the increase in temperature during and after can probably be attributed to heat flowing into the core from outer components.
Figure 4.24: The temperature in the core during and after irradiations at different beam offsets.

Figure 4.25: The temperature in the inner jacket during and after irradiations at different beam offsets.

Figure 4.25 shows that the biggest temperature increase in the inner jacket occurs when the beam is 9 mm offset. When the beam is centred on the core at 0 mm offset, the inner jacket increases in temperature then remains constant over the next 100 seconds,
implying that the heat flowing in from the core is balanced by the heat flowing out to the outer jacket. For 15 mm offset, the inner jacket shows a small increase in temperature (approximately 0.2 mK) during irradiation, and possibly an increase in temperature after irradiation, but with the larger uncertainties it is difficult to determine.

Figure 4.26: The temperature in the outer jacket during and after irradiations at different beam offsets.

In figure 4.25, the noise in the measurements is more apparent due to the smaller temperature increases observed. The outer jacket temperature increases by a similar amount for 0 mm and 9 mm offsets, but shows a larger increase for 15 mm offset. The beam passes through the front face of the outer jacket for all measured offsets, but when the beam is offset by 15 mm, it passes through the side wall too, increasing the dose deposited in outer jacket and leading to a larger temperature increase.

4.2 COMSOL Modelling

A model of the calorimeter and the proton beam was created in COMSOL: in this model the geometry of the calorimeter was simplified slightly because of computational memory constraints; and the proton beam was modelled as a cylindrical heat source with variable penumbrae.
4.2. COMSOL Modelling

Figure 4.27: Cross section (top view) of the calorimeter model created in COMSOL, with the three temperature output positions (CP3, CP5 and CP6) as described in section 4.2.2.

Figure 4.28: Cross section (side view) of the COMSOL calorimeter model.
4.2. Creating the Calorimeter and Beam

The calorimeter cross section was created in a single plane geometry, then revolved around the central axis to give a cylindrically symmetric shape. Having cylindrical symmetry reduced the time taken to run simulations (typically around 15 minutes per simulation). The drawback to this method was that the effects of the thermistors and wires, which are not cylindrically symmetric, could not be ascertained.

The model parameters shown in Table 4.2 were adjusted to fit the Clatterbridge data (and the Clatterbridge measurements were influenced by the outcome of simulations). The “beam-on” time was defined as being the difference between “t_start” and “t_end” so in the table below the beam came on 10 seconds after the start of the simulation then was turned off 29.7 seconds later. The beam was initially modelled as having a constant radius of 3 mm (it was later adjusted to fit with the measurements), and in Table 4.2 the offset is shown as 0 mm (i.e. centered on the calorimeter), although this was varied between 0-41 mm offset.

Table 4.2: COMSOL parameters that could be user-modified to model different beams

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>t_start</td>
<td>10.0 [s]</td>
</tr>
<tr>
<td>t_end</td>
<td>39.7 [s]</td>
</tr>
<tr>
<td>radius</td>
<td>3.0 [mm]</td>
</tr>
<tr>
<td>offset</td>
<td>0.0 [mm]</td>
</tr>
</tbody>
</table>

The beam cross-section was initially modelled as a symmetrical rectangle function (similar to a step function but with a step up at some x-value and a step down at some later x-value). This was labelled as the “rstep” function and had a lower limit of “-radius” and an upper limit of “radius” (as defined in Table 4.2). In later simulations the sharp steps were smoothed using the COMSOL “transition zone” feature, as shown in figure 4.29 to create penumbra. The user-defined transition zone describes the distance over which the function goes from zero to a maximum, with the radius at 50% height. For comparisons with the experimental results, the transition zone was adjusted to fit the penumbra observed in film measurements of the Clatterbridge beam (figure 4.6), as well as importing the Clatterbridge dose profile seen in figure 4.7 into COMSOL and
using it as the input for the beam cross-section.

Figure 4.29: Examples of the “rstep” function used to modify the beam cross-section and “beam on” time. (a) shows a step function with radius 2 mm and transition zone size 0 mm, producing sharp steps. In (b) the radius is still 2 mm but the transition zone has been changed to 2 mm, so the function starts increasing at 3 mm and reaches the maximum at 1 mm, smoothing the step function.

Similarly the “beam-on” time was modelled as an asymmetrical rectangle function, with the step up occurring at “t_start” and the step down occurring at “t_end”, and a transition time of 0.2 seconds. The transition zone was introduced for the “beam-on” time to eliminate a “ringing” effect that was occurring when the beam was switched on or off sharply.

The beam was modelled as a cylindrical heat source (the function “CylndrHeat”, defined in table 4.3), and the energy intensity input (function “int1”) was a SOBP depth dose curve (seen in Figure 4.30), obtained from experimentally measured data taken at Clatterbridge using 60 MeV protons. The function “CylndrHeat” was the input for the “user defined heat source”, Q [W/m³].

The different volumes and surfaces of the calorimeter were defined using the model definitions. These were used as inputs for material selection and heat transfer surfaces. The material properties for graphite were initially defined as given in Krauss’ paper [84]; later some of these material properties were optimised to match the beam data.

The heat transfer setting used was heat transfer in solids with surface-to-surface
4.2. COMSOL Modelling

Table 4.3: User-defined COMSOL variables

<table>
<thead>
<tr>
<th>Name</th>
<th>Expression</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>r</td>
<td>$\left( (x\text{-offset})^2 + z^2 \right)^{1/2}$</td>
<td>m</td>
</tr>
<tr>
<td>stepfnc</td>
<td>$r\text{step}(r \left[ 1/m \right])$</td>
<td>m</td>
</tr>
<tr>
<td>CylndrHeat</td>
<td>$\text{int1}(y+0.0875) \times \text{stepfnc} \times \text{rect1}(t) \times 5$</td>
<td></td>
</tr>
</tbody>
</table>

Figure 4.30: Percentage depth dose curve for the energy intensity input. The y-axis is the percentage of the average SOBP height, the x-axis is the depth in water.

radiation, with the outside of the calorimeter assumed to be thermally insulated, and an initial temp of 293.15 K. The surface-to-surface radiation equations used in the simulation were as shown in equation 4.2, derived in the COMSOL Heat Transfer Module User’s Guide [85].

\[
G = G_m(J) + G_{amb} + G_{ext} \\
G_{amb} = F_{amb}\sigma T_{amb}^4 \\
J = (1 - \epsilon)G + \epsilon \sigma T^4 \\
qu = \mathbf{n} \cdot (-k \nabla T) = \epsilon (G - \sigma T^4) \quad (4.2)
\]
Table 4.4: Material properties of graphite used in the simulation [84]

<table>
<thead>
<tr>
<th>Property</th>
<th>Name</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat capacity at constant pressure</td>
<td>$C_p$</td>
<td>712</td>
<td>$J/(kg \cdot K)$</td>
</tr>
<tr>
<td>Density</td>
<td>$\rho$</td>
<td>1840</td>
<td>$kg/m^3$</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>$k$</td>
<td>150</td>
<td>$W/(m \cdot K)$</td>
</tr>
<tr>
<td>Relative permeability</td>
<td>$\mu_r$</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Electrical conductivity</td>
<td>$\sigma$</td>
<td>$3 \times 10^3$</td>
<td>$S/m$</td>
</tr>
<tr>
<td>Relative permittivity</td>
<td>$\epsilon_r$</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Surface emissivity</td>
<td>$\epsilon_{rad}$</td>
<td>0.85</td>
<td>1</td>
</tr>
</tbody>
</table>

where $G$ is the total radiative flux, $G_m$ is the mutual heat flux coming from other surfaces in the model, $J$ is the radiosity (the sum of the reflected and emitted radiation), $G_{amb}$ is the ambient heat flux, $G_{ext}$ is heat flux from external sources (i.e. the cylinder of heat), $F_{amb}$ is the ambient view factor (the fraction of the field of view that is not covered by other boundaries), $\sigma$ is the Stefan-Boltzmann constant, $T_{amb}$ is the ambient temperature, $\epsilon$ is the emissivity, $q$ is the net inward radiative heat flux, $n$ is the normal vector on the boundary, $k$ is the thermal conductivity and $T$ is the temperature of the component.

The time-dependent simulation was run from 0 to 170 seconds, with output time steps of 0.5 s (and internal model stepping of 0.25 s).

4.2.2 Results

COMSOL automatically provides several standard visualisations of the effects of the cylinder of heat over the simulation time period, including the temperature distribution (seen in figure 4.31) and isothermal contours (figure 4.32).

These were useful for checking that the heat was being applied where it was expected, but it was difficult to compare different offsets and the impact of various parameters, so to provide results that were easier to compare, cut points were created at which the temperature variation with time could be plotted. Out of an initial selection of seven cut points (CPs) in different positions, three were chosen, at 5 mm offset (CP3), 10 mm offset (CP5) and 15 mm offset (CP6), which can be seen in figure 4.27.
4.2. COMSOL Modelling

Figure 4.31: Temperature distribution for a 4 mm diameter beam centred on the core (0 mm offset) with 3 mm penumbra

while an example of the variation of temperature over time for these cut points can be seen in figure 4.33.

Figure 4.33 shows that, similar to the measured results, when the beam is centred on the calorimeter the core rises in temperature most during the irradiation, then after irradiation the temperature decreases. The inner and outer jackets also increase in temperature during irradiation but the temperature remains relatively stable after irradiation, with a gradient of less than $10^{-3}$ mK/s, implying low net heat loss or gain.

Comparing Beam Diameter

Initially simulations were run such that the cylindrical heat source had no penumbra (transition zone size = 0 mm). The collimator used in the measurements had a diameter of 4 mm, but it was recognised that when the proton beam reached the calorimeter, the beam diameter was likely to be larger due to the effects of scattering in the air between the nozzle and the calorimeter. With this information, beams with radii 2, 3 and 4 mm were compared. Figure 4.34 shows the results of simulations these beam radii, all with
4.2. COMSOL Modelling

Figure 4.32: Isothermal contours for a 4 mm diameter beam centred on the core (0 mm offset) with 3 mm penumbra

Figure 4.33: Example of temperature variation with time for the three cut points, at 0 mm beam offset
the same value of power per unit volume, and the beam at 0 mm offset. However, it is quite difficult to compare the different beams in figure 4.34, because the total energy deposited is different for each beam diameter, and therefore the temperature reached in each component is different. To overcome this, scaling factors were applied which scaled the data from each beam radius by the maximum temperature in the core; the resulting graph can be seen in figure 4.35.

![Graph comparing temperature variation with time for different beam diameters](image)

Figure 4.34: Comparing the effect of changing the beam diameter on the temperature variation with time in the three calorimeter components: core (solid line), inner jacket (IJ, dotted line) and outer jacket (OJ, dashed line), at 0 mm offset.

Figure 4.35 shows that in comparison to beams with radii 3 mm and 4 mm, when the beam radius is 2 mm, the core drops more quickly in temperature. This is related to the lower temperature in the inner jacket, leading to a larger temperature difference and higher rate of heat loss from the core.

Using graphs like figure 4.35 at a variety of beam diameters, as well as at 9 and 15 mm beam offset, a comparison between the COMSOL and measurement data could be made and the most suitable beam diameters chosen.
Figure 4.35: The same raw data as in figure 4.34 but ‘normalised’ such that the peak temperature in the core = 1 for all beam diameters.

Comparing Beam Penumbra

A similar comparison can be drawn from looking at a fixed beam diameter but varying the size of the transition zone. The beam diameter was chosen to be 8 mm (radius 4 mm), and figures 4.36 compare transition zones of 0, 2 and 4 mm, where a 2 mm transition zone on a 4 mm radius beam describes a beam where the intensity starts to decrease 3 mm from the centre and reaches zero at 5 mm (as described in section 4.2.1)

In refining the model to include the effect of the beam penumbra, the dose curve seen in figure 4.7 was imported and used in the COMSOL model. However, one drawback to this method was that the curve only shows the dose profile at the front face of the calorimeter, rather than at the depth in graphite of the core where the protons would have undergone more scattering and thus the dose profile at the core may be somewhat different to that seen in figure 4.7. It was found that a wider beam gave a better fit to the data.
Comparing Emissivities

Several simulations were run comparing the effect of changing the emissivity from the suggested value of $\epsilon = 0.85$. The emissivity is a measure of how effective a surface is at emitting energy in the form of infra-red radiation, and varies between 0 (no radiation emitted) and 1 (perfect black body). These simulations were run with a beam diameter of 9 mm, with a penumbra width of 4 mm, at the three key offsets (0, 9, 15 mm), and comparing three different values of emissivity: $\epsilon = 0.5$, $\epsilon = 0.85$ and $\epsilon = 1$.

From figure 4.37 it can be seen that altering the emissivity at 0 mm beam offset results in a change in the gradient of the core post-heating temperature, with the lowest emissivity ($\epsilon = 0.5$) gradient being the shallowest. This corresponds to a slower rate of thermal energy loss, as would be expected from an object with a lower emissivity. The inner and outer jacket curves show a much smaller difference in their gradients between emissivities, by virtue of their lower temperatures. In addition to the change in gradient, a difference in the maximum temperature after heating is observed - this is due to the heat loss during the heating period, e.g. when the emissivity was set as $\epsilon = 0.5$, the core lost less heat during heating so the maximum temperature reached after
Figure 4.37: Comparing the effects of changing the emissivity on the core, inner jacket and outer jacket, at 0 mm beam offset heating was higher.

Figure 4.38: Comparing the effects of changing the emissivity on the three calorimeter components at 9 mm beam offset

At 9 mm beam offset (seen in figure 4.38), the inner jacket shows the biggest vari-
ation with emissivity, with the lower values of emissivity leading to smaller gradients after heating. Interestingly the core component shows very little variation with emissivity - when the emissivity is high, the larger heat loss from the core is balanced by the larger heat gain from the inner jacket; while when the emissivity is low, the core loses less heat to its surroundings but gains less heat from the inner jacket.

Figure 4.39: Comparing the effects of changing the emissivity on the three calorimeter components at 15 mm beam offset

When the beam is centred in the outer jacket at 15 mm beam offset (figure 4.39), although the variation in curves produced is more notable, it is at least in part due to the lower temperatures reached in all the components. As before, when the emissivity is low, the component that reaches the highest temperature has the slowest rate of heat loss, while the other components exhibit slower rates of heat gain.

Varying the emissivity between simulations has some impact on the maximum temperatures reached in each components after irradiation, but has more impact on the post-heating gradients. Comparing these post-heating gradients with those obtained in the measurements, the ones at $\varepsilon = 0.85$ seem to have the best fit.
4.3 Comparison of Measurements and Simulations

Comparison between the measurement data and results of simulations enabled the most suitable model parameters (listed in Table 4.5) to be chosen. The graphs of the COMSOL model predictions with these parameters have been overlaid with the measurement results (from section 4.1.5) and are shown for the core (Figure 4.40), inner jacket (Figure 4.41) and outer jacket (Figure 4.42) for three different beam offsets (0, 9 and 15 mm). In each case the x-axis shows the time measured in seconds, while the y-axis displays the temperature measured in Kelvin.

Table 4.5: Final COMSOL model parameters

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam radius</td>
<td>4.5 mm</td>
</tr>
<tr>
<td>Transition zone</td>
<td>8 mm</td>
</tr>
<tr>
<td>Graphite emissivity</td>
<td>0.85</td>
</tr>
</tbody>
</table>

![Graph of temperature vs. time with measurement and simulation data for different beam offsets.](image)

Figure 4.40: Comparison between the measurement results (solid line) and the COMSOL simulations (dashed line) at different offsets in the core.

The agreement between the measurements and COMSOL simulations is generally very good. In the core component, the measured temperature rise at 9 mm beam offset...
4.3. Comparison of Measurements and Simulations

Figure 4.41: Comparison between the measurement results and the COMSOL simulations at different offsets in the inner jacket.

Figure 4.42: Comparison between the measurement results and the COMSOL simulations at different offsets in the outer jacket.

is approximately 0.25 mK higher than would be expected from the simulations, while a similar difference in temperature rise is seen in the outer jacket at 15 mm beam offset. The outer jacket response is most likely to be caused by the simplifications in
the shape of the calorimeter that were made in order to minimise computational time. Other than these two exceptions, the agreement between the initial rise in temperature due to radiation is excellent.

Looking at the drifts in temperature post-irradiation, the agreement again is very good for most, the main exception being the 9 mm offset beam in the inner jacket, where the measured temperature drops quicker then the simulation predicted - this could be due to conductive heat loss along the wires and through the PCB.

### 4.4 Clatterbridge Beam Line Geometry

Validating the beam line geometry was a valuable aspect of the work presented in this thesis. Originally a diagrammatic outline of the Clatterbridge beam line geometry was provided by Dr. Colin Baker [86] (Fig. 4.43) who has previously worked on Monte Carlo simulations of the beam line. This was converted into TOPAS code (Appendix B), with the help of example files found within the TOPAS program, taking special care with the non-trivial transformations of the coordinate system and geometrical definitions.

![Diagram of the Clatterbridge beam line](image)

**Figure 4.43:** Diagram of the Clatterbridge beam line as provided by Colin Baker [86].

The numbers on figure 4.43 correspond to the components within the beamline and are listed below:

1. Pre-collimator
2. $1^{st}$ scattering foil
3. Stopper
4. 2\textsuperscript{nd} scattering foil
5. Kapton window
6. Range shifter
7. Modulator wheel
8. 1\textsuperscript{st} Collimator
9. Ion chamber
10. 2\textsuperscript{nd} Collimator
11. Nozzle
12. Reference plane
13. Water phantom

However, when clarifying details with Dr. Andrzej Kacperek (Head of Physics at CCC), it became clear there were inconsistencies between two versions of the diagram provided by Baker, information given by Kacperek and information in a paper written by Bonnett [87]. Using measured data and photographs (provided by A. Kacperek [88], see figure 4.45) the resulting geometry can be seen in Figure 4.44.

Figure 4.44: Diagram of the TOPAS beamline and calorimeter created in the current work.
Figure 4.45: Picture of the Clatterbridge beamline taken from above. The beam comes from the vacuum tube on the left, through the range modulation wheel, aluminium piping and ion chambers visible on the right.

Once the beam line had been constructed then the passage of protons through the beam line could be simulated. A water phantom was created: in measurements of the depth dose curve a cubic phantom is used with dimensions of 30 x 30 x 30 cm$^3$, but due to scoring methodologies a cylindrical phantom was chosen with a radius of 5 cm and a length of 7 cm. Within this phantom a smaller scoring region was defined with a 2.65 mm radius (to mimic the radius of the collecting volume of a Markus chamber that was used for the measured data) and 35 mm length (to cover the proton beam range). The length was divided up into 500 bins, each 0.07 mm. This was small enough to get a good depth dose curve, but large enough that it did not take too long to run to get a smooth curve.

Scoring within this region showed that the efficiency of the beam line was approximately 1%, i.e. for every 100 histories started at the beginning of the beam line, only
1 of those reached the phantom. This necessitated long run times in order to reduce uncertainties and increase reliability.

The calculated range of the proton beams was compared to NIST (National Institute of Standards and Technology) data [89]. Once the beam energy had been calculated, it was noticed that when the measured data and the TOPAS data were normalised at 10 mm depth, there was a significant difference in the height, with the TOPAS data approximately 15% higher in the peak.

This difference arises because the Clatterbridge beam is not perfectly monoenergetic; there is a spread of energies produced by the cyclotron. This beam energy spread has not been directly measured for the Clatterbridge beam so the only solution is to simulate a range of beam energy spreads and pick the one that best fits the measurement data. Paganetti [90] describes using a beam energy spread of 0.5 MeV for a 160 MeV beam at the Harvard Cyclotron Laboratory. Although there is no reason for the beam energy spread to scale with energy (since it depends mainly on the structure of the accelerator and beamline), it is expected that the Clatterbridge beam energy spread will be of the same order of magnitude, so five simulations were run with beam energy spreads up to 0.5 MeV. With further optimisation, and a slight modification of the beam energy from 60.00 MeV to 62.63 MeV to better match the range in measured data, the optimal beam energy spread was found to be 0.31 MeV. Note that TOPAS requires the beam energy spread as a percentage of the mean energy rather than an absolute number; thus, the input beam energy spread was 0.4950%.

In addition no measurement of the angular distribution of the source, or of any possible contamination particles, was available so these were initially assumed to be zero, and the results obtained from simulations suggested any impact was negligible.

4.4.1 Modulated Beam

Once the beam parameters had been adjusted to give the best fit to the measured data, an additional parameter file was added to the beamline to insert a range modulation wheel (known as a propeller in TOPAS). The propeller was created using data provided by CCC as specified during the manufacture of range modulation wheel 769. For a full
SOBP the range modulation wheel consists of 32 Lucite steps, each 0.84 mm thicker than the previous (equivalent to a thickness of 1 mm in water), with span angles shown in Appendix B, table B.1.

The model was run with a beam energy of 62.63 MeV and a beam energy spread of 0.31 MeV, scoring the dose in a cylindrical volume with 2.65 cm radius, with the length split into 500 scoring bins, each 0.07 mm long. The TOPAS propeller was set to rotate 45 degrees about the z-axis in 1 degree steps, with $1.4 \times 10^6$ histories per rotation, so $6.3 \times 10^7$ histories in total. The result and comparison with measured data is shown in figure 4.46, with the TOPAS data normalised at a depth of 9 mm.

![Figure 4.46: Plot of the measured modulated depth dose curve against the TOPAS simulated curve using a propeller.](image)

The normalised results show some difference between the measured and simulated data in the distal end of the SOBP region, with the simulated results dropping below the measurements. In order to investigate whether these differences were due to an effect caused by the way TOPAS deals with range modulation wheels, simulations were run where the modulator wheel was replaced by slabs of PMMA corresponding to each step thickness. Thirty-three simulations were run, with a slab thickness corresponding

\[^1 \text{TOPAS does not include Perspex in its list of default material parameters so Lucite was used instead and the density was changed to 1.18g/cm}^3.\]
to every one of the 32 slabs and the air gap (no slab). Figure 4.47 shows the unweighted (raw data) Bragg peak curves obtained.

Figure 4.47: Unweighted Bragg peak curves obtained from placing progressively thicker slabs of PMMA in the beam path. Each scoring bin was 0.07 mm thick.

The unweighted Bragg peak curves were then weighted according to the span angle and summed to obtain the SOBP. Figure 4.48 shows that the shape of this SOBP agrees well with the previous TOPAS simulation using the propeller, with the dip in dose at the end of the range, and although there are some differences in dose in the distal region, it is clear that it still does not match well to the measured data.

However, by adjusting the weightings of just four of the Bragg peaks (corresponding to adjusting the span angles of some of the steps, see Appendix B, table B.1 for the adjusted span angles), very good agreement with the measurement data could be obtained, as seen in figure 4.49 - it is likely that either there are some small differences in the simulated and actual beamlines that lead to the differences seen, or the range modulator wheel measurements (particularly span angles) were not precisely implemented during manufacture, and thus the new weightings are likely to be more representative of the actual wheel used. Using individual slabs, rather than the propeller, allowed the span angles to be adjusted manually.
Figure 4.48: The Bragg peaks from figure 4.47 were weighted and summed to give the SOBP dose distribution.

Figure 4.49: By adjusting the weightings (span angles) of the four highest energy Bragg peaks used to obtain figure 4.48, a very accurate match to the measured data can be obtained.
4.5 Implications and Conclusions

From figures 4.50, 4.51 and 4.52 it can be seen that the experimental and theoretical results qualitatively agree with each other but that there are some small quantitative differences. These differences can, at least in part, be explained by the simplifications made in the model of the calorimeter and proton beam geometry.

However, it is pleasing that even in a fairly simplistic model of the calorimeter, similar heat flows and responses to irradiation occur. The model provides a good foundation for looking at the response of scanned beams, which can be thought of as individual offset beams occurring one after another.
4.5. Implications and Conclusions

Figure 4.51: Comparison between the measurement results and COMSOL simulations in the different calorimeter components at 9 mm offset

Figure 4.52: Comparison between the measurement results and COMSOL simulations in the different calorimeter components at 15 mm offset
Chapter 5

Scanning Beams

The method of beam delivery for the Prague beam differs from the Clatterbridge beam. In the Prague beam, the protons are formed into a narrow beam with focusing magnets, then sweeping magnets “pull” the beam from side to side. Spot irradiations are possible with the sweeping magnets turned off, but in addition a continuous line scan can be achieved in any direction, a two-dimensional square at a given proton beam range, and a three-dimensional cube, composed of multiple two-dimensional squares with different ranges (achieved by changing the beam energy).

The Clatterbridge beam line does not have scanning magnets and produces only static beams. However, by moving the target instead of the beam, an approximation to a scanned beam could be produced for experimental purposes.

5.1 COMSOL Simulations

Most of the simulations were performed with static beams, to correspond with the measurements done at Clatterbridge. However, some did look at a moving beam using a time-dependent offset, both with the position changing smoothly and as a step function.

This was achieved by changing the “offset” parameter to a variable which took its values from a table of time against offset. The offset varied linearly with time from 0 to 20 mm (in 1 mm steps) over the time range 2.5 s to 22.5 s (corresponding to an average speed of 1 mm/s). The function derived from this table of values could be interpolated linearly or “nearest neighbor”, the former creating a smoothly scanning beam whereas
Figure 5.1: The difference between a linear (a) and a nearest neighbour (b) interpolation. The linear interpolation (a) exemplifies a continuously varying beam position while the nearest neighbour interpolation (b) exemplifies a step function change in the beam position, similar to the “jogging” done in experiments at Clatterbridge.
5.1. COMSOL Simulations

the latter created a beam that moved in steps, spending one second at each position. This difference is illustrated in figure 5.1.

The resulting differences in the temperature-time graphs from these two methods of interpolation can be seen in figure 5.2. There are only small differences in the shape of the resulting graphs, with a larger rise in temperature in the core with the nearest neighbour interpolation of approximately 0.013 mK equating to a 1.5% difference, while in the inner jack the difference is even smaller at approximately 0.6% and approximately 0.3% in the outer jacket. These small differences are due to the differing amounts of time the beam is directly heating each component, and they give confidence that the “jogging” method used at Clatterbridge is a close approximation to a real scanned proton beam.

![Temperature-time graphs](image)

Figure 5.2: The resulting differences between the nearest neighbour (NN) and linear interpolations for the scanned heat source.

The shape of the curves resulting from the scanned beam can be compared to those with static beams seen in section 4.2. The previously sharp peaks seen as the beam is switched off are replaced by smooth curves as the beam steadily moves across one component to the next. The beam starts centred on the core and moves outwards at a speed of 1 mm/s, so the core increases in temperature for approximately 14 seconds, but towards the end of that period it is at a decreasing rate as only part of the beam
passes through the core. After that period the core decreases in temperature as heat is lost to the inner (and outer) jacket.

In the inner jacket, the temperature increases for approximately 20 seconds starting as soon as the beam is switched on since it has to pass through the jacket to reach the core, so an initial linear rise in temperature is seen before the rate of temperature rise increases as the beam directly heats the side walls of the inner jacket, then (similarly to the core) increasing at a decreasing rate as the beam continues to move outwards, passing through less of the jacket. After the beam is switched off the temperature in the inner jacket decreases by approximately 0.025 mK over the following two minutes - at a slower rate than in the core since although energy is being lost to the outer jacket, it is also being received from the core.

The temperature in the outer jacket shows a similar pattern to the inner jacket with an initial increase in temperature at a rate of 0.46 K/minute increasing to 1.60 K/minute once the position of the beam means more of the outer jacket is being heated. The outer jacket increases in temperature over a period of approximately 23 seconds (longer than the beam-on time), since the temperature of the outer jacket continues to rise after direct beam heating due to heating from the core and inner jacket.

5.1.1 Direct vs Indirect Heating

Originally the scanning COMSOL simulations were set up such that the scanning heat source passed through (directly heating) the cut points (points of measurement), as visualised in figure 5.3. This created peaks in the resulting temperature-time graphs where the graphite was directly heated before the heat redistributed to the rest of the component. The effect can be seen in figure 5.4 where direct heating (DH) is compared to indirect heating (IH).

The networked nature of the thermistors in the inner and outer jackets mean that this effect is unlikely to be seen (since the thermistors are placed equidistantly around the circumference), but it may be possible to observe this effect in the core where the core 1 and core 2 thermistors are independent (see section 5.2.1).
5.1. COMSOL Simulations

Figure 5.3: Figure 4.27 has been overlaid with green arrows showing the two directions of heat source scanning with the cut points either being directly heated (DH) or indirectly heated (IH).

Figure 5.4: COMSOL data comparing the difference between direct heating (DH) and indirect heating (IH) in the core, inner and outer jackets.
5.2 Clatterbridge Measurements

As stated in Chapter 4, the calorimeter was mounted on a carriage which could be moved perpendicular to the beam direction by a user-specified distance (to give the static offset measurements) and could also be “jogged” continuously (repeatedly moving a short user-specified distance of 1 mm, resting at each position for approximately 1 second) to give a simple approximation to a scanned beam.

5.2.1 Core Thermistor Differences

During analysis of the Clatterbridge data it was noticed that during static offset measurements the response between the two thermistors in the core was slightly different, as seen in figure 5.5. Although the variation due to noise is large (blue crosses), there is a definite effect that during irradiations, the temperature in the core 2 thermistor is slightly higher than in the core 1 thermistor. A scaled version of the core 1 raw temperature curves has been overlaid (red diamonds) to put the difference into context of when the irradiations are occurring.

![Graph showing difference between core 1 and core 2 thermistors](image)

Figure 5.5: The difference between the core 1 and core 2 thermistors during 3 irradiations at 3 mm offset, with scaled core 1 thermistor data overlaid to show when irradiations were occurring
5.2. Clatterbridge Measurements

This effect becomes more pronounced at 7 mm offset (see figure 5.6), but is smaller at 9 mm offset (figure 5.7), while at 0 mm offset no such effect occurs. These differences only occur during the irradiation itself and no difference is obvious post-irradiation. This evidence all points towards the cause being that the core 2 thermistor is in the beam during irradiation, which would cause the temperature in the thermistor to be higher when the beam is on.

Figure 5.6: The difference between the core 1 and core 2 thermistors during 3 irradiations at 7 mm offset, with scaled core 1 thermistor data overlaid to show when irradiations were occurring

The differences in temperature are small, less than 0.1 mK, and too small to observe on a graph like figure 4.14, but it was recognised that this difference between the two thermistors could be used during scanned beam measurements to work out which direction the beam is scanning. This effect was not seen in the inner and outer jackets due to the thermistors being in a network, as opposed to independent as in the core (see section 3.4.2).

Although the “jogging” measurements at Clatterbridge did not give a high enough dose to the calorimeter to provide a meaningful analysis, this method of studying the difference between the core thermistors could be used. While all the offset measure-
5.3 Prague Measurements

The calorimeter measurements performed at the Proton Therapy Center (PTC), Prague are split into four groups of irradiations: spots (similar to what was done in Clat-
5.3. Prague Measurements

Figure 5.8: The difference between the core 1 and core 2 thermistors during an irradiation where the calorimeter was being “jogged” from the core centre (0 mm) to 25 mm offset, with scaled core 1 thermistor data overlaid to show when the irradiation was occurring.

5.3.1 Calorimeter Set Up

The calorimeter was placed on a typical patient flat-bed couch, and secured in place using custom-made fixings. At the beginning of each measurement session the couch was transported from an equipment store room to the treatment room using a robotic couch. Once in the treatment room, the couch was transferred to a robotic arm which can be seen in figures 5.9 and 5.10.

Figure 5.11 shows the alignment lasers used to position the calorimeter at the isocentre of the beam, while figure 5.12 shows a close-up of the calorimeter set up as it would be during beam delivery.
5.3. Prague Measurements

Figure 5.9: Photograph in the treatment room of the patient couch attached to a robotic arm with the calorimeter on the couch (second from right). The (pale blue) beam nozzle can be seen on the left of the picture near the (red & grey) vacuum pump on the floor.

5.3.2 Film Measurements

Similarly to the method described in section 4.1.1 radiochromic film was affixed to the front face of the calorimeter and irradiated with a 180 MeV proton beam. The film itself can be seen in figure 5.13 and the analysed dose curve in figure 5.14.

As expected the dose profile in the uncollimated PTC beam was larger (with a FWHM of approximately 13 mm) than the CCC beam (FWHM of approximately 7 mm) which was collimated close to the measurement point.

5.3.3 Single Spots

The calorimeter was irradiated with a 180 MeV beam, centred on the core, of 100 MU delivered in 200 spots (0.5 MU/spot) which corresponds to a dose of approximately 3.6 Gy. It was delivered over a period of approximately 4 seconds. The dose profile for the single spots can be seen in figure 5.14. For the calorimeter measurements graphite plates 20A and 1A (thickness 20 mm and 1 mm respectively) were placed up against
Figure 5.10: Photograph similar to figure 5.9 from a different angle with the robotic arm having been moved so that the beam passes through the water tank on the right of the calorimeter. A monitor chamber can be seen on a tripod in front of the nozzle.

Figure 5.11: Photograph of the calorimeter being aligned using lasers.

the front face of the calorimeter so the core would not be in the build up region. The temperature against time graph can be seen in figure 5.15 which shows results from
5.3. Prague Measurements

Figure 5.12: Photograph of (from left to right) the beam nozzle, monitor chamber and calorimeter.

Figure 5.13: Film irradiated in the uncollimated proton beam at PTC Prague.

the core and inner jacket thermistors averaged over 5 irradiations.

The results from the spot irradiation in Prague are broadly similar to the results from the Clatterbridge irradiations, although with higher dose rates over a shorter length of time. Using the original COMSOL model with the same model parameters but modifying it so that the measured dose profile was used and the outer jacket was set to be a constant temperature of 28°C, there was found to be good agreement between
Figure 5.14: The film in figure 5.13 was analysed using ImageJ \cite{83} to produce this dose profile curve.

Figure 5.15: The temperature variation with time in the core and inner jacket thermistors during a centralised (0 mm offset) spot irradiation.

The COMSOL model shows very good agreement to the temperature rise that occurs during irradiation, with the relative amplitude of the steps in excellent agreement
Figure 5.16: The same graph as seen in figure 5.15 overlaid with the COMSOL model predictions for the ‘Core’ (CP3) and ‘Inner Jacket’ (CP5).

with the measured data. However, while the gradient of the temperature in the core after irradiation is slightly steeper than that seen in the measurements, the inner core temperature gradient is slightly shallower, which (as previously) may be due to the minor simplifications in the model.

5.3.4 Line Scans

At the PTC Prague, line scans are achieved by using the sweeping magnets to pull a monoenergetic beam in any particular lateral direction. As described in section 5.3.3, the dose is delivered in spots so the beam is not continuous during the scanning - each spot is delivered in a different position along the length of the scan. The beam was swept across the calorimeter in the x (left to right from the beam perspective) and y (top to bottom) directions as well as at a 45° angle (top left to bottom right) over a length of 15 cm (± 7.5 cm from the isocentre, which had been aligned with the calorimeter core), with each scan taking approximately 6 seconds. An initial irradiation was carried out with radiochromic film taped to the front face of the calorimeter to check that the expected distribution was being achieved. In addition, 4 mm of graphite build-up plates were placed in front of the film to replicate the approximately 4 mm depth in graphite
5.3. Prague Measurements

of the core, so that when the film was later scanned it would replicate the spot size incident on the core - the results of this irradiation can be seen in figure 5.17 (the build up plate has been removed). The beam energy was 226 MeV for these measurements; 12 MU was delivered per spot (approximately 0.4 Gy/spot) and the spot spacing was 2 mm.

Figure 5.17: Photograph of the calorimeter with radiochromic film taped to the front face after irradiation of three line scans in the x, y and 45° directions.

In the x-direction the thermistor results were as expected with a rise in temperature during irradiation and a decrease in temperature after the beam was switched off. However, for the 45° and y-direction scans, a peak in temperature was observed in the core 1 thermistor (see figure 5.18).

The core 2 thermistor also displayed some unusual behaviour in the y-direction scans with a small peak, then a drop in temperature, followed by a rebound back to align with the temperature seen in the x and 45° directions (see figure 5.19).

Apart from the peaks, the scans in the three different directions show very good agreement post-irradiation, with less than 1% difference between 15 and 60 seconds for the core 1 thermistor, while the core 2 thermistor shows a maximum difference of less than 1.5% (due to the scan in the x direction).
5.3. Prague Measurements

Figure 5.18: The temperature as measured by the core 1 thermistor before, during and after line scans in the x, y and 45° directions.

Figure 5.19: The temperature as measured by the core 2 thermistor before, during and after line scans in the x, y and 45° directions.

The line scans were carried out in quasi-adiabatic mode so there are no results for the outer jackets but the inner front and inner back jackets do not display the same ‘peaking’ behaviour (see figures 5.20 and 5.21). There are larger differences in the post-
irradiation temperatures in the inner jacket than in the core thermistors; up to 3% in the inner front jacket and 3.5% in the inner back jacket.

Figure 5.20: The temperature as measured by the inner front jacket thermistors before, during and after line scans in the x, y and 45° directions.

Figure 5.21: The temperature as measured by the inner back jacket thermistors before, during and after line scans in the x, y and 45° directions.
To understand and explain the cause of the unusual behaviours seen in the core thermistors, some further detail is required. The core 1 and core 2 thermistors show no peaks when the beam is scanning in the x-direction. When the beam scans in the y-direction (top to bottom) the core 1 thermistor reaches a peak temperature that is 50% higher than that reached in the x-direction, while the core 2 thermistor displays a peak that is only 2% higher than in the x-direction and a dip that is 8% lower. In the case of the core 1 thermistor the peak in the y-direction scan occurs approximately 0.5 seconds before the maximum temperature reached in the x-direction, while in the core 2 thermistor, this difference in peak temperature timings between the x and y directions is nearly 2 seconds.

These differences between the core 1 and core 2 thermistors can be explained by the direct heating effect of the beam on the thermistor. No peaks are seen when the beam scans in the x-direction, since neither thermistor is in the central high-dose region of the beam, i.e. neither the core 1 nor core 2 thermistor are directly irradiated. The peaks in the core 1 and core 2 curves occur at different times relative to the x-direction beam which gives an indication of where each thermistor is located - since the time gap between the core 2 thermistor peaks is larger than the core 1 thermistor, the core 2 thermistor must be irradiated first i.e. it is located at the top of the core. This means that as the beam scans in the y-direction from the top to the bottom of the calorimeter, the core 2 thermistor is directly heated before most of the core which would lead to the peak in temperature during direct irradiation, a drop in temperature when it is no longer in the middle of the beam then an increase in temperature as the rest of the core is heated. Conversely, the core 1 thermistor is directly heated after the beam has passed through most of the core, so the peak in temperature due to direct heating is added to the temperature increase occurring due to heating from the core. The effect can be thought of as a convolution between the normal heating that occurs in the x-direction scan and a (near) delta function due to the effect of direct heating, which occurs at different times relative to the normal heating curve in the core 1 and core 2 thermistors.

One slightly puzzling feature is that when the line scan is at 45°, a mini peak is seen in the core 1 thermistor (approximately 4.5 times smaller than the peak seen in
the y-direction), yet no mini dip is seen in the core 2 thermistor. The most likely explanations for this is that either the dip is too small to be captured by the fairly coarse reading frequency of the calorimeter (relative to the time-scales of the effects) or there is a slight misalignment of the calorimeter in the beam.

### 5.3.5 Two-Dimensional Layer

A 6 x 6 cm square, rotated in the x-y plane by 45°, was created in the treatment planning system and delivered with a beam energy of 180 MeV (the ‘raw’ 226 MeV beam was degraded within the beamline to reduce the proton beam energy). The calorimeter was in quasi-adiabatic mode with graphite build-up plates (reference numbers 20A and 1A) placed in front of the calorimeter providing an extra 21 mm of graphite for the beam to pass through (to avoid the build-up region in the core). The results for each thermistor (seen in figure 5.22) were averaged over 4 irradiations.

![Figure 5.22: The temperature in the core (C1 and C2) and inner jacket (IF and IB) thermistors before, during and after irradiation of a two dimensional layer.](image)

The core 1 and core 2 results are in very good agreement with one another with the difference always less than 2%, and the inner front and inner back jacket thermistors show equally good agreement. Unlike in the line scans, no detail within the curves is seen, such as direct irradiation of the thermistors - therefore the time taken to paint
5.3. Prague Measurements

the layer is much quicker than the response time of the calorimeter.

One point of interest with the curves is seen when the irradiation region is expanded. Figure 5.23 shows the same graph as figure 5.22 but focused on the time period between 12 and 15 seconds. It shows that there is a clear split between the core and inner jacket thermistors, with the inner jacket thermistors reaching the same temperature as the core thermistors but the increasing sigmoid function having a shallow (and near-constant) gradient over the irradiation period, while the core thermistor temperatures exhibit a steeper sigmoid function behaviour.

Figure 5.23: The same data as seen in figure 5.22 but looking solely at the period of irradiation.

The reason for this behaviour is due to the method of beam delivery and specifically the order in which the spots are deposited. The beam spots are delivered one row at a time starting from the top left and working across the row before ‘snaking’ onto the next row. This means the beam will start directly heating the inner jacket before it directly heats the core (since the jacket covers a large area lateral to the beam than the core), and conversely will keep heating the inner jacket after it has stopped heating the core (although the effect is less obvious at the end since more time has elapsed for heat to flow from the inner jacket into the core).

The difference between a scanned and scattered beam delivery for a layer irradiation
can be estimated by comparing figure 5.22 to the results of a large field irradiation in COMSOL as shown in figure 5.24. The beam radius was chosen such that the beam area is equivalent to a 6 x 6 cm square i.e. 36 cm² so the total energy deposited in the calorimeter would be the same in each case.

![Figure 5.24: The same data as shown in figure 5.22 overlaid with the COMSOL model predictions for a 36 cm² field.](image)

The response of the measurements and the model over the irradiation period is very similar, with the gradient of the post irradiation drift in the core slightly steeper in the COMSOL simulations than in the thermistor data, especially 50 seconds after irradiation. This could be due to the simplifications in the COMSOL model, for example excluding the PCB which could heat up more than the core during the irradiation and then transfer heat to the core via the thermistor leads. It can be concluded that the response of the calorimeter in a single layer scanned beam irradiation is not significantly different to a similar scattered beam field.

### 5.3.6 Three-Dimensional Volumes

A 6 x 6 x 6 cm cube was created in the treatment planning system consisting of 12 two-dimensional square x-y layers, with the energy of the beam decreasing between each layer to create the full three-dimensional shape. The number of spots in each layer...
is not constant; instead the spot placement is optimised by the treatment planning system to ensure as flat a profile as possible. The calorimeter was in quasi-adiabatic mode, with multiple graphite build-up plates (20A, 20B, 20C, 20D, 20E, 10A, 10B, 5A, 2A, 1A, 0.5F, total thickness of 128.5 mm) in front to ensure that the core was in the centre of the cube.

![Figure 5.25](image)

Figure 5.25: Temperature rise in the core resulting from a 6 x 6 x 6 cm cube delivered in 12 layers, with 7 independent irradiations.

Figure 5.25 shows that as each layer is delivered (starting from the highest energy, back-most layer), the core temperature rises, initially by 0.5 mK in the first layer, then by 0.65 mK, 0.3 mK, 0.3 mK, 0.25 mK, 0.3 mK, 0.05 mK, then any further rises are smaller than the noise. The different layers within the cube are delivered with different intensities, to ensure the resulting dose distribution has a flat profile. Since each beam will contribute to the dose before (but not after) the Bragg peak, the beams with shorter ranges will necessarily have a lower intensity than those with longer ranges. Only 7 out of the 12 layers delivered are visible within the core - the remaining 5 energy layers are deposited in the graphite in front of the core. The time period over which the temperature rises in each layer occur is approximately 0.75 seconds (consistent with that seen in the single layer, section 5.3.5) equivalent to three readings, so it is possible for a reading to be timed such that it occurs just before or just after the beam is turned.
on - the delivery time for a layer is of the same order of magnitude as the sampling rate.

The time between consecutive layers (or steps) generally varies between 4.5 seconds and 6 seconds, although the 4th irradiation shows some delay in the 5th layer, probably due to the feedback mechanism of the beamline. In addition it can be seen that the layers are delivered at slightly different times in different irradiations, which makes taking an average of the irradiations difficult as later layers will be averaged out and the steps will be less visible.

The results from different thermistors were compared by averaging over the three irradiations with the best agreement in step timings (in order not to ‘smear out’ the steps), this comparison is seen in figure 5.26.

![Figure 5.26: Average temperature rise resulting from a 6 x 6 x 6 cm cube delivered in 12 layers as measured by the core 1, core 2, inner front and inner back jacket thermistors.](image)

The agreement between the core 1 and core 2 thermistors is very good; after 33 seconds (the third step) the difference between the thermistors is less than 1%. The inner jacket thermistors exhibit a larger difference, but this can be explained with an understanding of the dose delivery. For each energy layer the inner back jacket is positioned further back along the dose profile (relative to the beam) than the inner front jacket.
This results in the back jacket being closer to the Bragg peak and receiving a higher dose (while the depth dose curve covers both jackets), and explains the larger steps seen in the back jacket compared to the front jacket in the first 5 steps.

In the 6th step the inner front jacket rises more than the inner back jacket (0.28 mK compared to 0.24 mK), while in the 7th step the increase in temperature in the inner front jacket is approximately 1.2 mK whereas in the back jacket it is barely visible above the noise. This is where the Bragg peak is positioned such that the inner back jacket is either only partially in the beam (6th step) or in the next layer it is not being directly irradiated at all (7th step). Similarly to the layer irradiations, no detail within the curves is seen due to direct irradiation of the thermistors.

The results from the ‘cube’ scanned beam irradiation can again be compared to a similar scattered beam simulation in COMSOL, seen in figure 5.27.

Figure 5.27: The same data as shown in figure 5.26 overlaid with the COMSOL quasi-adiabatic (QA) model predictions for a 36 cm$^2$ field.

The irradiation time length for the COMSOL simulations was chosen to match the time from the first step that is seen in the thermistor data to the last (40.5 seconds), but note that in the PTC measurements the beam continues to irradiate components (and build-up plates) in front of the core beyond this time. This is a possible contributory factor to the differences seen between the simulation and measurement data in
5.4. Implications and Conclusions

There is good agreement initially in the core although in the simulation the temperature drops slightly quicker than seen in the measurements; given that this happens on a long timescale in comparison to the irradiation it will not affect the extrapolation to mid-run, although it could play a role for longer irradiations. However, the agreement in the inner jacket is worse. The simulation predicts that the temperature rise in the inner jacket should be higher (by approximately 0.15 mK) than is observed within the calorimeter. Once the beam is switched off the gradients in the inner jacket simulations and measurement are similar which gives credibility to the modelling of the heat flows. There are larger differences between the model and the measurements in the multi-layer cube than in the single layer (figure 5.24) but it seems that the current operation of the calorimeter is not significantly affected by the scanned beams.

5.4 Implications and Conclusions

The line scans performed at Clatterbridge were at too low a dose rate to see meaningful temperature rises in the calorimeter components, but some information could be extracted by looking at the difference between the core thermistors, including the direction of scan.

The irradiations performed at the PTC, Prague provided lots of new information about the response of the calorimeter that had never previously been observed. The spot irradiations were similar to that conducted at Clatterbridge but at higher dose rates, and there was a similar level of agreement with the COMSOL model.

From the line scans in the y-direction, unusual behaviour due to direct heating was observed in both core thermistors (as well as large differences between the thermistors) but neither were seen to have a lasting impact on the measured temperature of the calorimeter and these effects had disappeared less than two seconds after the start of the temperature rise due to irradiation.

The agreement between thermistors in the two-dimensional layer irradiations was very good, and no unusual “peaking” behaviour was observed, unlike in the line scans. There was a difference between the core and inner jacket thermistors in length of irradiation time, which was explained by the method of beam delivery. Comparison
with the COMSOL model for a radiation field with the same area produced good agreement.

The variable beam delivery timings of each step in the three-dimensional cube irradiations posed some challenges in combing irradiations to calculate averages. The agreement between the core thermistors was excellent and the inner jacket thermistors exhibited behaviour that was consistent with expectations.
Chapter 6

Calorimeter Correction Factors

Various correction factors need to be applied to results obtained from the calorimeter, the main one being a factor converting dose-to-graphite to dose-to-water. Two correction factors that were investigated in the course of this work using TOPAS were (i) the compensated gap correction factor, $k_{\text{gap}}$, and (ii) the volume averaging correction factor, $k_{\text{vol}}$.

A simplified model of the calorimeter was created in TOPAS, which removed the PCB (printed circuit board) and changed the slanted edges of the outer jacket and mantle to straight edges. The graphite used for the calorimeter in both simulations had density 1.83 g/cm$^3$ with a mean excitation energy of 78 eV.

6.1 Gap Corrections

The gap correction factor ($k_{\text{gap}}$) calculates the effect of the vacuum gaps within the calorimeter on the dose to the core. Ideally the quantity measured would be the temperature rise in a solid graphite phantom; the vacuum gaps are introduced to minimise the heat flow between different components within the calorimeter. However, these vacuum gaps can affect the path of the proton beams and potentially lead to less scattering, which may affect the dose deposited in the core.

To investigate this effect, and evaluate a value for $k_{\text{gap}}$, a “compensated” model of the calorimeter was created in TOPAS (see figure 6.1). In this compensated calorimeter, the vacuum gaps are replaced with graphite. In addition, the position of the core is...
Figure 6.1: Schematic side-view cross-section diagrams of (a) normal calorimeter geometry (b) compensated calorimeter geometry and (c) volume averaging calorimeter geometry. Grey shaded areas are graphite; the lighter grey in (b) shows the added graphite although in the simulation the graphite used for both dark and light grey is the same. The white areas are the vacuum gaps. N.B. not to scale.

adjusted so the protons pass through the same thickness of graphite as they would in the non-compensated model. A 40 cm thick “backing block” was added behind the calorimeter to provide material for backscatter.

The correction factor was evaluated at five different beam energies of 60 MeV, 100 MeV, 150 MeV, 190 MeV and 230 MeV in order to assess whether the factor was energy dependent. The beam energies were chosen to cover the typical range of energies used in medical treatments at proton therapy centres. The beam was defined to be monoenergetic, with a circular diameter of 3 cm centred on the calorimeter and no angular dispersion.

For the 60 MeV beam, \(1.02 \times 10^9\) histories were run in both geometries, spread over 6 simultaneous simulations with different starting seeds. Figure 6.2 shows an example visualisation of the results. Similarly \(1.02 \times 10^9\) histories were run for each geometry in the 150 MeV beam, spread over 6 simulations with different starting seeds. For the 100 MeV, 190 MeV and 230 MeV simulations, \(5.1 \times 10^8\) histories were run over 3 simulations. The mean and standard deviation of the mean were calculated for each energy, with the standard deviations of each geometry being added in quadrature to

\[\text{The standard deviation of the mean is defined as the standard deviation divided by the square root of the number of values i.e. } \frac{s}{\sqrt{N}}\]
get the final result.

![Figure 6.2: Side view of the compensated calorimeter geometry after undergoing 60 MeV proton irradiation (5cm long coordinate axes are noted for scale). The blue lines are proton paths, the green lines are electron paths](image)

Defining $k_{\text{gap}}$ as the dose to the core in the compensated geometry, divided by the dose to the core in the normal geometry, the calculated results are shown in table 6.1 for each energy.

Table 6.1: Calculated gap correction factors ($k_{\text{gap}}$) for a range of proton energies between 60 MeV and 230 MeV with $k = 1$ uncertainties.

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>$k_{\text{gap}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>1.00064(08)</td>
</tr>
<tr>
<td>100</td>
<td>1.00107(05)</td>
</tr>
<tr>
<td>150</td>
<td>1.00211(14)</td>
</tr>
<tr>
<td>190</td>
<td>1.00277(13)</td>
</tr>
<tr>
<td>230</td>
<td>1.00359(15)</td>
</tr>
</tbody>
</table>
A plot of these correction values with their uncertainties (for $k = 1$) is shown in figure 6.3. The correction factor has a quadratic dependence on energy, ranging from 0.06% above unity at 60 MeV to 0.36% above unity at 230 MeV.

![Plot of correction factor vs. energy (MeV)](image)

Figure 6.3: A plot of the variation of the gap correction factor with energy (MeV), with associated errors on each value. Uncertainties are given at the 1σ level.

Protons scatter more in graphite than in a vacuum (see section 2.1.2), so in the normal calorimeter geometry with vacuum gaps, there will be fewer protons and secondary particles scattered into the core, leading to a lower dose in the core. This is supported by the simulations which show that the core dose is higher when the vacuum gaps are filled with graphite, i.e. in the normal calorimeter geometry, some of the secondary dose is “missing”, and the gap correction factor quantifies this missing dose.

This explanation also accounts for the dependence of the correction factor on energy since the higher the primary proton energy, the higher the energy of the secondary scattered particles [18], so the larger the correction.

### 6.1.1 Simulations Without Nuclear Interactions

To check that this assumption was correct, simulations were run with the nuclear interactions switched off. This is possible using the modular physics lists in TOPAS, see section 3.6.2. Only the simulation for the highest proton energy of 230 MeV was run...
as this is where the secondary particles (and therefore nuclear interactions) have the biggest impact. $1.53 \times 10^8$ histories were run in total for each geometry (it was possible to run fewer histories than in the original simulation since the standard deviation was smaller). The result can be seen in figure 6.4, which shows that excluding nuclear interactions from the simulations, eliminates the difference between the normal and compensated geometry, and hence the nuclear interactions are the cause of the gap correction factor.

![Figure 6.4: A plot showing the same data as in figure 6.3 with the addition of a “no nuclear interaction” simulation run at 230 MeV.](image)

### 6.1.2 Simulations At 2 cm Water Equivalent Depth

The 150 MeV and 230 MeV simulations were ran as before, but modified to include a 10 mm graphite block in front of the calorimeter, such that the centre of the core was at 23.1 mm water-equivalent depth. This was done in order to provide more realistic correction factors since in “real-life” measurements with the calorimeter, the core is positioned at between 2 and 3 cm water-equivalent depth.

The correction factors are significantly larger with the build up plates since there are more secondary particle produced from nuclear reactions at deeper depths. This level of secondary particle build-up, producing a correction greater than 0.5% at the highest
6.2. Volume Averaging Corrections

Figure 6.5: A plot showing the same data as in figure 6.3 with the addition of a “build-up plate” simulation run at 150 and 230 MeV.

energies, is a concern for a primary standard, which should ideally have correction factors closer to unity. However, this knowledge can help inform designs of a future proton calorimeter.

6.2 Volume Averaging Corrections

The volume averaging correction factor ($k_{\text{vol}}$) accounts for the difference between the measurements of dose to the entire core, and what is actually required; i.e. the dose at a point in the centre of the core. Since it is not possible to calculate the dose at an infinitesimally small point, a small volume consisting of a sphere of radius 0.25 mm was chosen. This provided a balance between being small enough to approximate as a point, and being large enough so that suitable simulation statistics were obtained in a reasonable length of time.

The calorimeter geometry file was altered to define the small sphere ($r = 0.25$ mm) in the centre of the core, and the control file was adapted such that two scoring files were produced: one for dose to the whole core and one for dose in the small region. Six simulations were run with different starting seeds and the sum of the dose deposited
in each region was scored. A mean dose and the standard deviation of the mean were calculated for each region and compared to the difference between the regions. The number of histories was increased until the difference between the doses was at least double the largest of the standard deviations - it was found that 6 runs of \(1.7 \times 10^8\) histories were sufficient.

Two monoenergetic beam energies were chosen: \(60\) MeV and \(230\) MeV; and the beam itself had (as previously) a circular diameter of \(3\) cm centred on the calorimeter and no angular dispersion. Defining \(k_{\text{vol}}\) as the dose to the small sphere, divided by the dose to the core, it was calculated for \(60\) MeV to be:

\[
k_{\text{vol}} = 0.99936(44) \quad (6.1)
\]

and for \(230\) MeV to be:

\[
k_{\text{vol}} = 1.00515(154) \quad (6.2)
\]

The volume averaging correction factor occurs because the gradient of the depth dose curve is not constant. This means that the dose at the centre of the core, which would ideally be measured, is not equal to the averaged dose across the core, i.e. that which is actually measured. Measurements made using the calorimeter are usually done with a build-up plate in front of the calorimeter to avoid the build-up region, seen in the \(200\) MeV Bragg curve of figure 6.6 where the derivative of the gradient is initially negative. By placing build-up plates in front of the calorimeter, the effective point of measurement is moved back, i.e. increased in depth, where the gradient is approximately constant. However, care must be taken to avoid moving the measurement point too far back, since near the Bragg peak the derivative of the gradient is positive.

The \(60\) MeV simulations were run without build-up plates, with the centre of the calorimeter core at a depth of \(4.133\) mm. From figure 6.6 at this depth, the gradient of the depth dose curve is already increasing to the Bragg peak. Simply using the Bragg peak curve and comparing the value of the dose at the depth of graphite which would correspond to the centre of the core, to the average over the depths of graphite corresponding to the physical size of the core gives results where the dose at the “centre” is \(0.07\%\) lower than the average dose over the “core”, which is consistent with the simulation results.
6.3 Implications and Conclusions

TOPAS was used to calculate two correction factors for the graphite calorimeter: the gap correction factor ($k_{\text{gap}}$) and the volume averaging correction factor ($k_{\text{vol}}$).

The vacuum gaps in the calorimeter structure result in less scattering of secondary particles into the core so $k_{\text{gap}}$ is greater than one and has a strong energy dependence. The correction factor ranges from approximately 0.06% above unity for 60 MeV proton beams to approximately 0.36% above unity for 230 MeV proton beams. The effect was shown to be due to the nuclear interactions within the graphite, and became more critical when the calorimeter was positioned further back within the depth dose curve using build-up plates.

To calculate $k_{\text{vol}}$ the dose deposited in the core was compared to the dose deposited
in a 0.25 mm radius sphere at the centre of the core. This correction factor, required to account for the curvature of the Bragg peak curve, was much smaller than the correction needed for the vacuum gaps, at approximately 0.06% below unity for 60 MeV proton beams to approximately 0.5% above unity for 230 MeV proton beams.
Chapter 7

Conclusions

With the advent of two new clinical proton machines in the UK which will come online in the next two years, this work is likely to become increasingly important, in particular regarding the advantages of proton therapy in the cancer treatment of infants and children. Using scanned proton beams (as opposed to scattered beams) is likely to become the main method of proton therapy delivery and therefore it is essential to gain an understanding of the response of primary standard calorimeters in this modality.

The first measurements carried out in small static proton beams in the graphite calorimeter have been detailed and the thermistor signals analysed to gain an understanding of the resulting heat flows. A model of the calorimeter has been built in COMSOL which largely predicts the temperature variations with time in the core, inner and outer jacket based solely on radiative heat transfer. The differences between the simulations and the measurements are attributable to the simplifications made to the geometry of the outer jacket and the conductive heat flows through the wires and PCB. A new design of an NPL graphite calorimeter for photon beams where there is no PCB within the calorimeter is in the early stages of testing and with adjustments for the differing geometries this COMSOL model should provide a useful simulation tool for investigating the heat flows in the new calorimeter.

This thesis also describes and analyses the first use of the NPL proton calorimeter in a scanned proton beam. Four different methods of beam delivery (spots, lines, layers and cubes) and their effect on the calorimeter have been discussed. Any unusual behaviour has been explained and the measurements have been validated using the COMSOL model. The behaviour of the calorimeter in the line scans, layers and scanned
beam is compatible with the method of determining the absorbed dose by extrapolating the pre- and post- temperature drifts to mid-run. In addition a possible method for determining the direction of scanning by looking at the difference between the core thermistors has been provided.

A Monte Carlo simulation method has been used to calculate the gap correction factor and the volume averaging correction factor for the NPL graphite calorimeter in proton beams. The gap correction factor \((k_{\text{gap}})\) is greater than unity, as expected due to the lower numbers of scattered particles into the core volume than would be expected in a solid graphite block. It increases with energy from 1.00064(08) at 60 MeV to 1.00359(15) at 230 MeV. The volume averaging correction factor is less than unity at 60 MeV where \(k_{\text{vol}} = 0.99936(44)\), and greater than unity at 230 MeV where \(k_{\text{vol}} = 1.00515(154)\). These are due to the curvature of the Bragg peak depth dose distribution at the depth in graphite at which the core is located.

This work gives us confidence that the response of the calorimeter in scanned beams is not significantly dissimilar to that in scattered beams and we can continue to use the same method for calculating absorbed dose.
Appendix A

Appendix A - Clatterbridge Analysis

A.1 Film Analysis

The film measurements taken at Clatterbridge were scanned using an Epson 10000XL scanner, and analysed using ImageJ. Cuts were taken at different angles to confirm the symmetry of the beam, for example in figure A.1, cuts were taken at 45° and 90°, producing very similar profiles.

In addition, the calorimeter was initially placed at a distance of approximately 32 cm from the collimator (instead of the 20 cm used in the main set of measurements). However, on visually inspecting the film produced (see figure A.2), the shorter distance was chosen as being more suitable for the measurements.

Comparing the analysed films in figure A.3 it can be seen that the larger distance between the collimator and front face of the calorimeter gives much wider penumbra due to the increased scattering in air.

A.2 Calorimeter Analysis

The temperature in the core, inner jacket and outer jacket when the beam is centred on the core (0 mm offset) can be seen in figure A.4. Averaging and standard deviation
A.2. Calorimeter Analysis

Figure A.1: Dose curves from different angle cuts showing the symmetry of the beam.

Figure A.2: Films irradiated in the proton beam at CCC. The film on the left was done with the calorimeter at a distance of 20 cm from the collimator, while the film on the right was taken at a distance of 32 cm.

was processed over 2 irradiations from period 5, and 6 irradiations from period 30.

The temperature in the core, inner jacket and outer jacket when the beam is 3 mm offset can be seen in figure A.5. These data are based on 3 irradiations from period 30. Note that the standard deviations are smaller than in figure A.4 (0 mm offset) since the irradiations were carried out one after another, when the air temperature and pressure were near identical, whereas the data that went into the 0 mm offset results were taken at 4 separate times.

The temperature in the core, inner jacket and outer jacket when the beam is 7 mm
A.2. Calorimeter Analysis

Figure A.3: Dose curves produced from the analysis of the films seen in figure A.2. The distances in the legend refer to the collimator-to-calorimeter distance.

Figure A.4: The results of irradiations at 0 mm offset. These data are based on 3 irradiations from period 2.

The temperature in the core, inner jacket and outer jacket when the beam is 9 mm offset can be seen in figure A.6. These data are based on 3 irradiations from period 30.
A.2. Calorimeter Analysis

Figure A.5: The results of irradiations at 3 mm offset.

The temperature in the core, inner jacket and outer jacket when the beam is 11 mm offset can be seen in figure A.8. These data are based on 3 irradiations from period 30.

Figure A.6: The results of irradiations at 7 mm offset.

The temperature in the core, inner jacket and outer jacket when the beam is 13 mm offset can be seen in figure A.9. These data are based on 5 irradiations from periods 3
A.2. Calorimeter Analysis

Figure A.7: The results of irradiations at 9 mm offset.

Figure A.8: The results of irradiations at 11 mm offset.

The temperature in the core, inner jacket and outer jacket when the beam is 15 mm offset can be seen in figure A.10. These data are based on 3 irradiations from period 30.

The temperature in the core, inner jacket and outer jacket when the beam is 18 mm
A.2. Calorimeter Analysis

Figure A.9: The results of irradiations at 13 mm offset.

Figure A.10: The results of irradiations at 15 mm offset.

offset can be seen in figure A.11. These data are based on 2 irradiations from period 3.
Figure A.11: The results of irradiations at 18 mm offset.
Appendix B

Appendix B - TOPAS Code

B.1 Code for the Clatterbridge beamline

d:Ge/World/HLX =0.75 m
d:Ge/World/HLY =0.75 m
d:Ge/World/HLZ =1.5 m

# Default Beam position
s:Ge/BeamPosition/Parent ="World"
s:Ge/BeamPosition/Type ="Group"
d:Ge/BeamPosition/TransX =0.0 m
d:Ge/BeamPosition/TransY =0.0 m
d:Ge/BeamPosition/TransZ =-1.5 m
d:Ge/BeamPosition/RotX =0.0 deg
d:Ge/BeamPosition/RotY =0.0 deg
d:Ge/BeamPosition/RotZ =0.0 deg

b:Ts/ShowHistoryCountOnSingleLine = "False"
i:So/Default/NumberOfHistoriesInRun = 10
Ts/PauseForGeant4Commands ="BeforeSequence"
i:Ts/ShowHistoryCountAtInterval = 0

#Source
s:So/Default/Type = "Beam"
s:So/Default/Component = "BeamPosition"
s:So/Default/BeamParticle = "proton"
d:So/Default/BeamEnergy = 62.2 MeV
u:So/Default/BeamEnergySpread = 0.0
s:So/Default/BeamShape = "Ellipse"
d:So/Default/BeamHWX = 3 mm
d:So/Default/BeamHWY = 3 mm
d:So/Default/BeamAngularSpreadX = 0.00 rad
B.1. Code for the Clatterbridge beamline

```plaintext
d:So/Default/BeamAngularSpreadY = 0.00 rad
s:So/Default/BeamXYDistribution = "Flat"
# Flat or Gaussian (s.d. is 0.65cm in x and y)

s:Ge/VacuumBox/Parent = "World"
s:Ge/VacuumBox/Type = "TsBox"
d:Ge/VacuumBox/TransX = 0.0 cm
d:Ge/VacuumBox/TransY = 0.0 cm
d:Ge/VacuumBox/TransZ = -134.0 cm
d:Ge/VacuumBox/RotX = 0.0 deg
d:Ge/VacuumBox/RotY = 0.0 deg
d:Ge/VacuumBox/RotZ = 0.0 deg
s:Ge/VacuumBox/Material = "Vacuum"
d:Ge/VacuumBox/HLX = 5.25 cm
d:Ge/VacuumBox/HLY = 5.25 cm
d:Ge/VacuumBox/HLZ = 16.0 cm
s:Ge/VacuumBox/Color = "green"
s:Ge/VacuumBox/DrawingStyle = "Wireframe"

s:Ge/PreCollimator/Parent = "VacuumBox"
s:Ge/PreCollimator/Type = "TsBox"
d:Ge/PreCollimator/TransX = 0.0 cm
d:Ge/PreCollimator/TransY = 0.0 cm
d:Ge/PreCollimator/TransZ = -14.1 cm
d:Ge/PreCollimator/RotX = 0.0 deg
d:Ge/PreCollimator/RotY = 0.0 deg
d:Ge/PreCollimator/RotZ = 0.0 deg
s:Ge/PreCollimator/Material = "Brass"
d:Ge/PreCollimator/HLX = 5.25 cm
d:Ge/PreCollimator/HLY = 5.25 cm
d:Ge/PreCollimator/HLZ = 0.5 cm

s:Ge/PreCollimatorHole/Parent = "PreCollimator"
s:Ge/PreCollimatorHole/Type = "TsCylinder"
d:Ge/PreCollimatorHole/TransX = 0.0 cm
d:Ge/PreCollimatorHole/TransY = 0.0 cm
d:Ge/PreCollimatorHole/TransZ = 0.0 cm
d:Ge/PreCollimatorHole/RotX = 0.0 deg
d:Ge/PreCollimatorHole/RotY = 0.0 deg
d:Ge/PreCollimatorHole/RotZ = 0.0 deg
s:Ge/PreCollimatorHole/Material = "Vacuum"
d:Ge/PreCollimatorHole/RMin = 0.0 cm
d:Ge/PreCollimatorHole/RMax = 0.3 cm
d:Ge/PreCollimatorHole/HL = 0.5 cm
d:Ge/PreCollimatorHole/SPhi = 0.0 deg
d:Ge/PreCollimatorHole/DPhi = 360.0 deg
s:Ge/PreCollimatorHole/DrawingStyle = "FullWireFrame"
```
s:Ge/ScatteringFoil1/Parent = "VacuumBox"
s:Ge/ScatteringFoil1/Type = "TsBox"
d:Ge/ScatteringFoil1/TransX = 0.0 cm
d:Ge/ScatteringFoil1/TransY = 0.0 cm
d:Ge/ScatteringFoil1/TransZ = -11.59875 cm
d:Ge/ScatteringFoil1/RotX = 0.0 deg
d:Ge/ScatteringFoil1/RotY = 0.0 deg
d:Ge/ScatteringFoil1/RotZ = 0.0 deg
s:Ge/ScatteringFoil1/Material = "SFTungsten"
d:Ge/ScatteringFoil1/HLX = 5.25 cm
d:Ge/ScatteringFoil1/HLY = 5.25 cm
d:Ge/ScatteringFoil1/HLZ = 0.00125 cm

########################################
sv:Ma/SFTungsten/Components = 1 "Tungsten"
uv:Ma/SFTungsten/Fractions = 1 1.0
d:Ma/SFTungsten/Density = 19.3 g/cm3
d:Ma/SFTungsten/MeanExcitationEnergy = 727.0 eV
s:Ma/SFTungsten/DefaultColor = "orange"
i:Ma/Verbosity = 1
d:Ma/Brass/Density = 8.75 g/cm3
d:Ma/Air/Density = 1.203 mg/cm3
d:Ma/Aluminum/Density = 2.69 g/cm3
d:Ma/Kapton/Density = 1.42 g/cm3
d:Ma/Mylar/Density = 1.38 g/cm3

########################################

s:Ge/Stopper/Parent = "VacuumBox"
s:Ge/Stopper/Type = "TsCylinder"
d:Ge/Stopper/TransX = 0.0 cm
d:Ge/Stopper/TransY = 0.0 cm
d:Ge/Stopper/TransZ = 10.67 cm
d:Ge/Stopper/RotX = 0.0 deg
d:Ge/Stopper/RotY = 0.0 deg
d:Ge/Stopper/RotZ = 0.0 deg
s:Ge/Stopper/Material = "Brass"
d:Ge/Stopper/RMin = 0.0 cm
d:Ge/Stopper/RMax = 0.2855 cm
d:Ge/Stopper/HL = 0.33 cm
d:Ge/Stopper/SPhi = 0.0 deg
d:Ge/Stopper/DPhi = 360.0 deg
s:Ge/Stopper/DrawingStyle = "Solid"

s:Ge/ScatteringFoil2/Parent = "VacuumBox"
s:Ge/ScatteringFoil2/Type = "TsBox"
B.1. Code for the Clatterbridge beamline

```plaintext
d:Ge/ScatteringFoil2/TransX = 0.0 cm
d:Ge/ScatteringFoil2/TransY = 0.0 cm
d:Ge/ScatteringFoil2/TransZ = 11.00125 cm
d:Ge/ScatteringFoil2/RotX = 0.0 deg
d:Ge/ScatteringFoil2/RotY = 0.0 deg
d:Ge/ScatteringFoil2/RotZ = 0.0 deg
s:Ge/ScatteringFoil2/Material = "SFTungsten"
d:Ge/ScatteringFoil2/HLX = 5.25 cm
d:Ge/ScatteringFoil2/HLY = 5.25 cm
d:Ge/ScatteringFoil2/HLZ = 0.00125 cm

s:Ge/KaptonWindow/Parent = "World"
s:Ge/KaptonWindow/Type = "TsBox"
d:Ge/KaptonWindow/TransX = 0.0 cm
d:Ge/KaptonWindow/TransY = 0.0 cm
d:Ge/KaptonWindow/TransZ = -117.9975 cm
d:Ge/KaptonWindow/RotX = 0.0 deg
d:Ge/KaptonWindow/RotY = 0.0 deg
d:Ge/KaptonWindow/RotZ = 0.0 deg
s:Ge/KaptonWindow/Material = "Kapton"
d:Ge/KaptonWindow/HLX = 5.25 cm
d:Ge/KaptonWindow/HLY = 5.25 cm
d:Ge/KaptonWindow/HLZ = 0.00125 cm
s:Ge/KaptonWindow/Color = "red"
s:Ge/KaptonWindow/DrawingStyle = "Solid"

s:Ge/Nozzle/Parent = "World"
s:Ge/Nozzle/Type = "TsBox"
d:Ge/Nozzle/TransX = 0.0 cm
d:Ge/Nozzle/TransY = 0.0 cm
d:Ge/Nozzle/TransZ = -3.705 cm
d:Ge/Nozzle/RotX = 0.0 deg
d:Ge/Nozzle/RotY = 0.0 deg
d:Ge/Nozzle/RotZ = 0.0 deg
s:Ge/Nozzle/Material = "Air"
d:Ge/Nozzle/HLX = 10.0 cm
d:Ge/Nozzle/HLY = 10.0 cm
d:Ge/Nozzle/HLZ = 64.3 cm
s:Ge/Nozzle/Color = "purple"
s:Ge/Nozzle/DrawingStyle = "Wireframe"

s:Ge/Aperture1/Parent = "Nozzle"
s:Ge/Aperture1/Type = "TsBox"
d:Ge/Aperture1/TransX = 0.0 cm
d:Ge/Aperture1/TransY = 0.0 cm
d:Ge/Aperture1/TransZ = -63.8 cm
```
B.1. Code for the Clatterbridge beamline

\[
\begin{align*}
    &d: Ge/\text{Aperture1/RotX} = 0.0 \text{ deg} \\
    &d: Ge/\text{Aperture1/RotY} = 0.0 \text{ deg} \\
    &d: Ge/\text{Aperture1/RotZ} = 0.0 \text{ deg} \\
    &s: Ge/\text{Aperture1/Material} = "\text{Brass}" \\
    &d: Ge/\text{Aperture1/HLX} = 10.0 \text{ cm} \\
    &d: Ge/\text{Aperture1/HLY} = 10.0 \text{ cm} \\
    &d: Ge/\text{Aperture1/HLZ} = 0.5 \text{ cm} \\
    &s: Ge/\text{Aperture1Hole/Parent} = "\text{Aperture1}" \\
    &s: Ge/\text{Aperture1Hole/Type} = "\text{TsCylinder}" \\
    &d: Ge/\text{Aperture1Hole/TransX} = 0.0 \text{ cm} \\
    &d: Ge/\text{Aperture1Hole/TransY} = 0.0 \text{ cm} \\
    &d: Ge/\text{Aperture1Hole/TransZ} = 0.0 \text{ cm} \\
    &d: Ge/\text{Aperture1Hole/RotX} = 0.0 \text{ deg} \\
    &d: Ge/\text{Aperture1Hole/RotY} = 0.0 \text{ deg} \\
    &d: Ge/\text{Aperture1Hole/RotZ} = 0.0 \text{ deg} \\
    &s: Ge/\text{Aperture1Hole/Material} = "\text{Air}" \\
    &d: Ge/\text{Aperture1Hole/RMin} = 0.0 \text{ cm} \\
    &d: Ge/\text{Aperture1Hole/RMax} = 2.0 \text{ cm} \\
    &d: Ge/\text{Aperture1Hole/HL} = 0.5 \text{ cm} \\
    &d: Ge/\text{Aperture1Hole/SPhi} = 0.0 \text{ deg} \\
    &d: Ge/\text{Aperture1Hole/DPhi} = 360.0 \text{ deg} \\
    &s: Ge/\text{Aperture1Hole/DrawingStyle} = "\text{FullWireFrame}" \\
    &s: Ge/\text{IonChamberMylar/Parent} = "\text{Nozzle}" \\
    &s: Ge/\text{IonChamberMylar/Type} = "\text{TsBox}" \\
    &d: Ge/\text{IonChamberMylar/TransX} = 0.0 \text{ cm} \\
    &d: Ge/\text{IonChamberMylar/TransY} = 0.0 \text{ cm} \\
    &d: Ge/\text{IonChamberMylar/TransZ} = -4.299 \text{ cm} \\
    &d: Ge/\text{IonChamberMylar/RotX} = 0.0 \text{ deg} \\
    &d: Ge/\text{IonChamberMylar/RotY} = 0.0 \text{ deg} \\
    &d: Ge/\text{IonChamberMylar/RotZ} = 0.0 \text{ deg} \\
    &s: Ge/\text{IonChamberMylar/Material} = "\text{Mylar}" \\
    &d: Ge/\text{IonChamberMylar/HLX} = 10.0 \text{ cm} \\
    &d: Ge/\text{IonChamberMylar/HLY} = 10.0 \text{ cm} \\
    &d: Ge/\text{IonChamberMylar/HLZ} = 0.001 \text{ cm} \\
    &s: Ge/\text{IonChamberAl/Parent} = "\text{Nozzle}" \\
    &s: Ge/\text{IonChamberAl/Type} = "\text{TsBox}" \\
    &d: Ge/\text{IonChamberAl/TransX} = 0.0 \text{ cm} \\
    &d: Ge/\text{IonChamberAl/TransY} = 0.0 \text{ cm} \\
    &d: Ge/\text{IonChamberAl/TransZ} = -4.2978 \text{ cm} \\
    &d: Ge/\text{IonChamberAl/RotX} = 0.0 \text{ deg} \\
    &d: Ge/\text{IonChamberAl/RotY} = 0.0 \text{ deg} \\
    &d: Ge/\text{IonChamberAl/RotZ} = 0.0 \text{ deg} \\
    &s: Ge/\text{IonChamberAl/Material} = "\text{Aluminum}" \\
    &d: Ge/\text{IonChamberAl/HLX} = 10.0 \text{ cm}
\end{align*}
\]
d:Ge/IonChamberAl/HLY = 10.0 cm
d:Ge/IonChamberAl/HLZ = 0.0001 cm

s:Ge/Aperture2/Parent = "Nozzle"
s:Ge/Aperture2/Type = "TsBox"
d:Ge/Aperture2/TransX = 0.0 cm
d:Ge/Aperture2/TransY = 0.0 cm
d:Ge/Aperture2/TransZ = 59.6 cm
d:Ge/Aperture2/RotX = 0.0 deg
d:Ge/Aperture2/RotY = 0.0 deg
d:Ge/Aperture2/RotZ = 0.0 deg
s:Ge/Aperture2/Material = "Brass"
d:Ge/Aperture2/HLX = 10.0 cm
d:Ge/Aperture2/HLY = 10.0 cm
d:Ge/Aperture2/HLZ = 3.9 cm

s:Ge/Aperture2Hole/Parent = "Aperture2"
s:Ge/Aperture2Hole/Type = "TsCylinder"
d:Ge/Aperture2Hole/TransX = 0.0 cm
d:Ge/Aperture2Hole/TransY = 0.0 cm
d:Ge/Aperture2Hole/TransZ = 0.0 cm
d:Ge/Aperture2Hole/RotX = 0.0 deg
d:Ge/Aperture2Hole/RotY = 0.0 deg
d:Ge/Aperture2Hole/RotZ = 0.0 deg
s:Ge/Aperture2Hole/Material = "Air"
d:Ge/Aperture2Hole/RMin = 0.0 cm
d:Ge/Aperture2Hole/RMax = 1.7 cm
d:Ge/Aperture2Hole/HL = 3.9 cm
d:Ge/Aperture2Hole/SPhi = 0.0 deg
d:Ge/Aperture2Hole/DPhi = 360.0 deg
s:Ge/Aperture2Hole/DrawingStyle = "FullWireFrame"

s:Ge/Collimator/Parent = "Nozzle"
s:Ge/Collimator/Type = "TsBox"
d:Ge/Collimator/TransX = 0.0 cm
d:Ge/Collimator/TransY = 0.0 cm
d:Ge/Collimator/TransZ = 63.9 cm
d:Ge/Collimator/RotX = 0.0 deg
d:Ge/Collimator/RotY = 0.0 deg
d:Ge/Collimator/RotZ = 0.0 deg
s:Ge/Collimator/Material = "Brass"
d:Ge/Collimator/HLX = 10.0 cm
d:Ge/Collimator/HLY = 10.0 cm
d:Ge/Collimator/HLZ = 0.4 cm

s:Ge/CollimatorHole/Parent = "Collimator"
s:Ge/CollimatorHole/Type = "TsCylinder"
B.1. Code for the Clatterbridge beamline

d:Ge/CollimatorHole/TransX = 0.0 cm
d:Ge/CollimatorHole/TransY = 0.0 cm
d:Ge/CollimatorHole/TransZ = 0.0 cm
d:Ge/CollimatorHole/RotX = 0.0 deg
d:Ge/CollimatorHole/RotY = 0.0 deg
d:Ge/CollimatorHole/RotZ = 0.0 deg
s:Ge/CollimatorHole/Material = "Air"
d:Ge/CollimatorHole/RMin = 0.0 cm
d:Ge/CollimatorHole/RMax = 1.0 cm
d:Ge/CollimatorHole/HL = 0.4 cm
d:Ge/CollimatorHole/SPhi = 0.0 deg
d:Ge/CollimatorHole/DPhi = 360.0 deg
s:Ge/CollimatorHole/DrawingStyle = "FullWireFrame"

s:Ge/Phantom/Parent = "World"
s:Ge/Phantom/Type = "TsCylinder"
d:Ge/Phantom/TransX = 0.0 cm
d:Ge/Phantom/TransY = 0.0 cm
d:Ge/Phantom/TransZ = 75.995 cm
d:Ge/Phantom/RotX = 0.0 deg
d:Ge/Phantom/RotY = 0.0 deg
d:Ge/Phantom/RotZ = 0.0 deg
s:Ge/Phantom/Material = "Water"
d:Ge/Phantom/RMin = 0.0 cm
d:Ge/Phantom/RMax = 16.926 cm
d:Ge/Phantom/HL = 15.0 cm
d:Ge/Phantom/SPhi = 0.0 deg
d:Ge/Phantom/DPhi = 360.0 deg
i:Ge/Phantom/RBins = 1
i:Ge/Phantom/PhiBins = 1
i:Ge/Phantom/ZBins = 500
s:Ge/Phantom/DrawingStyle = "FullWireFrame"

#############################################################################
# Graphics:
#############################################################################
# Graphics:
s:Gr/ViewA/Type = "OpenGL"
i:Gr/ViewA/WindowSizeX = 1024
i:Gr/ViewA/WindowSizeY = 768
d:Gr/ViewA/Theta = 270 deg
d:Gr/ViewA/Phi = -20 deg
s:Gr/ViewA/Projection = "Perspective"
d:Gr/ViewA/PerspectiveAngle = 30 deg
u:Gr/ViewA/Zoom = 4.
u:Gr/ViewA/TransX = 0.62995
u:Gr/ViewA/TransY = 0
b:Gr/ViewA/HiddenLineRemovalForTrajectories = "True"
B.2 Code for the Graphite Calorimeter

b:Gr/ViewA/IncludeAxes = "false"
#s:Gr/ViewA/AxesComponent = "Gantry"
d:Gr/ViewA/AxesSize = 0.5 m
b:Gr/Enable = "True"

d:Ge/World/HLX = 0.1 m
d:Ge/World/HLY = 0.1 m
d:Ge/World/HLZ = 0.1 m

i:Ma/Verbosity = 1
sv:Ma/Graphite/Components = 1 "Carbon"
uv:Ma/Graphite/Fractions = 1 1.0
d:Ma/Graphite/Density = 1.83 g/cm³
d:Ma/Graphite/MeanExcitationEnergy = 78.0 eV
s:Ma/Graphite/DefaultColor = "lightblue"

s:Ge/Calorimeter/Type = "Group"
s:Ge/Calorimeter/Parent = "World"
d:Ge/Calorimeter/TransX = 0.0 m
d:Ge/Calorimeter/TransY = 0.0 m
d:Ge/Calorimeter/TransZ = 0.0 m
d:Ge/Calorimeter/RotX = 0.0 deg
d:Ge/Calorimeter/RotY = 0.0 deg
d:Ge/Calorimeter/RotZ = 0.0 deg

s:Ge/BackingBlock/Parent = "Calorimeter"
s:Ge/BackingBlock/Type = "TsCylinder"
d:Ge/BackingBlock/TransX = 0.0 cm
d:Ge/BackingBlock/TransY = 0.0 cm
d:Ge/BackingBlock/TransZ = -16.3421 mm
d:Ge/BackingBlock/RotX = 0.0 deg
d:Ge/BackingBlock/RotY = 0.0 deg
d:Ge/BackingBlock/RotZ = 0.0 deg
s:Ge/BackingBlock/Material = "Graphite"
d:Ge/BackingBlock/RMin = 0.0 cm
d:Ge/BackingBlock/RMax = 50.0 mm
d:Ge/BackingBlock/HL = 10.0 mm
d:Ge/BackingBlock/SPhi = 0.0 deg
d:Ge/BackingBlock/DPhi = 360.0 deg
s:Ge/BackingBlock/DrawingStyle = "FullWireFrame"

s:Ge/Mantle/Parent = "Calorimeter"
B.2. Code for the Graphite Calorimeter

```plaintext
s:Ge/Mantle/Type = "TsCylinder"
d:Ge/Mantle/TransX = 0.0 cm
d:Ge/Mantle/TransY = 0.0 cm
d:Ge/Mantle/TransZ = 0.0 cm
d:Ge/Mantle/RotX = 0.0 deg
d:Ge/Mantle/RotY = 0.0 deg
d:Ge/Mantle/RotZ = 0.0 deg
s:Ge/Mantle/Material = "Graphite"
d:Ge/Mantle/RMin = 0.0 cm
d:Ge/Mantle/RMax = 50.0 mm
d:Ge/Mantle/HL = 6.3421 mm
d:Ge/Mantle/SPhi = 0.0 deg
d:Ge/Mantle/DPhi = 360.0 deg
s:Ge/Mantle/DrawingStyle = "FullWireFrame"

s:Ge/Vacuum3/Parent = "Mantle"
s:Ge/Vacuum3/Type = "TsCylinder"
d:Ge/Vacuum3/TransX = 0.0 cm
d:Ge/Vacuum3/TransY = 0.0 cm
d:Ge/Vacuum3/TransZ = 0.0154 mm
d:Ge/Vacuum3/RotX = 0.0 deg
d:Ge/Vacuum3/RotY = 0.0 deg
d:Ge/Vacuum3/RotZ = 0.0 deg
s:Ge/Vacuum3/Material = "Vacuum"
d:Ge/Vacuum3/RMin = 0.0 cm
d:Ge/Vacuum3/RMax = 20.0 mm
d:Ge/Vacuum3/HL = 4.77 mm
d:Ge/Vacuum3/SPhi = 0.0 deg
d:Ge/Vacuum3/DPhi = 360.0 deg
s:Ge/Vacuum3/DrawingStyle = "FullWireFrame"

s:Ge/OuterJacket/Parent = "Vacuum3"
s:Ge/OuterJacket/Type = "TsCylinder"
d:Ge/OuterJacket/TransX = 0.0 cm
d:Ge/OuterJacket/TransY = 0.0 cm
d:Ge/OuterJacket/TransZ = -0.289 mm
d:Ge/OuterJacket/RotX = 0.0 deg
d:Ge/OuterJacket/RotY = 0.0 deg
d:Ge/OuterJacket/RotZ = 0.0 deg
s:Ge/OuterJacket/Material = "Graphite"
d:Ge/OuterJacket/RMin = 0.0 cm
d:Ge/OuterJacket/RMax = 16.0 mm
d:Ge/OuterJacket/HL = 4.02 mm
d:Ge/OuterJacket/SPhi = 0.0 deg
d:Ge/OuterJacket/DPhi = 360.0 deg
s:Ge/OuterJacket/DrawingStyle = "FullWireFrame"
```
s:Ge/Vacuum2/Parent = "OuterJacket"
s:Ge/Vacuum2/Type = "TsCylinder"
d:Ge/Vacuum2/TransX = 0.0 cm
d:Ge/Vacuum2/TransY = 0.0 cm
d:Ge/Vacuum2/TransZ = 0.0028 mm
d:Ge/Vacuum2/RotX = 0.0 deg
d:Ge/Vacuum2/RotY = 0.0 deg
d:Ge/Vacuum2/RotZ = 0.0 deg
s:Ge/Vacuum2/Material = "Vacuum"
d:Ge/Vacuum2/RMin = 0.0 cm
d:Ge/Vacuum2/RMax = 14.0 mm
d:Ge/Vacuum2/HL = 3.2694 mm
d:Ge/Vacuum2/SPhi = 0.0 deg
d:Ge/Vacuum2/DPhi = 360.0 deg
s:Ge/Vacuum2/DrawingStyle = "FullWireFrame"

s:Ge/InnerJacket/Parent = "Vacuum2"
s:Ge/InnerJacket/Type = "TsCylinder"
d:Ge/InnerJacket/TransX = 0.0 cm
d:Ge/InnerJacket/TransY = 0.0 cm
d:Ge/InnerJacket/TransZ = 0.331 mm
d:Ge/InnerJacket/RotX = 0.0 deg
d:Ge/InnerJacket/RotY = 0.0 deg
d:Ge/InnerJacket/RotZ = 0.0 deg
s:Ge/InnerJacket/Material = "Graphite"
d:Ge/InnerJacket/RMin = 0.0 cm
d:Ge/InnerJacket/RMax = 11.75 mm
d:Ge/InnerJacket/HL = 2.5484 mm
d:Ge/InnerJacket/SPhi = 0.0 deg
d:Ge/InnerJacket/DPhi = 360.0 deg
s:Ge/InnerJacket/DrawingStyle = "FullWireFrame"

s:Ge/Vacuum1/Parent = "InnerJacket"
s:Ge/Vacuum1/Type = "TsCylinder"
d:Ge/Vacuum1/TransX = 0.0 cm
d:Ge/Vacuum1/TransY = 0.0 cm
d:Ge/Vacuum1/TransZ = -0.01735 mm
d:Ge/Vacuum1/RotX = 0.0 deg
d:Ge/Vacuum1/RotY = 0.0 deg
d:Ge/Vacuum1/RotZ = 0.0 deg
s:Ge/Vacuum1/Material = "Vacuum"
d:Ge/Vacuum1/RMin = 0.0 cm
d:Ge/Vacuum1/RMax = 8.75 mm
d:Ge/Vacuum1/HL = 1.75975 mm
d:Ge/Vacuum1/SPhi = 0.0 deg
d:Ge/Vacuum1/DPhi = 360.0 deg
s:Ge/Vacuum1/DrawingStyle = "FullWireFrame"
B.3 Range Modulation Wheel Weights

Figure B.1 explains the range modulation wheel (RMW) properties given in table B.1. Since the RMW has 4 lines of symmetry, parameters only need to be specified for \( \frac{1}{8} \) of the wheel and repeated as appropriate.

s:Ge/Core/Parent = "Vacuum1"
s:Ge/Core/Type = "TsCylinder"
d:Ge/Core/TransX = 0.0 cm
d:Ge/Core/TransY = 0.0 cm
d:Ge/Core/TransZ = 0.0 mm
d:Ge(Core)/RotX = 0.0 deg
d:Ge/Core/RotY = 0.0 deg
d:Ge/Core/RotZ = 0.0 deg
s:Ge/Core/Material = "Graphite"
d:Ge/Core/RMin = 0.0 cm
d:Ge/Core/RMax = 8 mm
d:Ge/Core/HL = 1.02275 mm
d:Ge/Core/SPhi = 0.0 deg
d:Ge/Core/DPhi = 360.0 deg
s:Ge/Core/DrawingStyle = "FullWireFrame"
Figure B.1: Schematic diagram of a range modulator wheel. One blade is shaded to show how the thickness of the wheel varies with each step - the darker colours indicate thicker PMMA. The steps numbers 1-14 are labelled, from thinnest to thickest, with step 0 being the air gap. Note this diagram only has 14 steps whereas the RMW used in the experiments has 32 steps.
Table B.1: Properties of the Clatterbridge range modulation wheel (RMW). These data corresponds to a 45° section of the RMW, see figure B.1.

<table>
<thead>
<tr>
<th>Step Number</th>
<th>Thickness (mm)</th>
<th>Span Angle (deg)</th>
<th>Adjusted Span Angle (deg)</th>
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Appendix C

Appendix C - Presentations and Papers

C.1 Conferences Attended

Surrey University PGR Conference 2013 (Guildford, UK)
PTCOG-52 2013 (Essen, Germany) - educational workshop and conference
PGBioMed 2013 (Guildford, UK)
PCRD 2014 - lectures
AAPM Summer School 2015 (Colorado, USA)

C.2 Presentations

Surrey University PGR Conference, February 2014 “Characterisation of a Graphite Calorimeter in Proton Pencil Beams” - poster presentation, awarded 2nd place
PPRIG, March 2014 (London, UK) “Graphite Calorimetry in Scanned Proton Beams” - oral presentation
ESTRO-33, April 2014 (Vienna, Austria) “Initial Characterization of a Graphite Calorimeter in a Proton Pencil Beam” - poster presentation
Surrey University PGR Conference, April 2015 “Characterisation of a Primary Standard Calorimeter for Scanned Proton Beam Therapy” - oral presentation, received 75
out of a total possible of 80 marks from the judges

3rd ESTRO Forum, April 2015 (Barcelona, Spain) “Graphite Calorimetry in Proton Pencil Beams” - poster presentation

PTCOG-54, May 2015 (California, USA) “Heat Transfer Modelling for Graphite Calorimetry in Narrow Proton Beams Using Simulations & Measurements” - poster presentation

NPL Group Seminar, March 2015 (London, UK) “Monte Carlo Modelling using TOPAS” - oral presentation


PPRIG, September 2015 (London, UK) “Heat Transfer Modelling for Proton Beam Therapy in a Graphite Calorimeter” - poster presentation

UCL Monte Carlo meeting, April 2015 (London, UK) “Monte Carlo Modelling of the Clatterbridge Beamline in TOPAS” - oral presentation

ICDA-2, July 2016 (Guildford, UK) “TOPAS Calculated Correction Factors for the NPL Proton Calorimeter” - oral presentation

### C.3 Published Papers


ICDA-2 2016 conference paper “Monte Carlo Calculated Correction Factors for the NPL Proton Calorimeter” - to be submitted to Radiation Physics and Chemistry
HEAT TRANSFER MODELLING FOR PROTON BEAM THERAPY IN A GRAPHITE CALORIMETER

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Abstract – Based on experiments, Monte Carlo and finite element simulations, this work contributes to the characterization of the NPL (National Physical Laboratory) graphite calorimeter in scanned proton beams. Agreement between the models and experimental data is generally good. A more accurate heat source is being created for the finite element model from the validated Monte Carlo simulation of the Clatterbridge beam line, which will improve the model and our understanding of the calorimeter.

I. INTRODUCTION

Proton beam radiotherapy is a method of cancer treatment which has recently gained considerable media attention. In order to optimise treatment outcome and patient safety, accurate radiation dose measurement is required. The NPL (National Physical Laboratory) primary standard level graphite calorimeters, instruments which measure the temperature rise due to energy deposition by the beam, are capable of determining absorbed dose to water, the quantity of interest, with the necessary accuracy for passively scattered proton beam therapy [1]. Using experimental data, Monte Carlo and finite element simulations, this work aims to understand how the NPL calorimeter responds to off-axis proton beams, in order to gain an understanding of how it will respond in scanned proton beams.

II. METHODS

The core of the NPL proton calorimeter consists of a graphite cylinder, 16 mm in diameter and 2 mm in height. This core is surrounded by two graphite jackets, separated by thin sprung polystyrene supports, with a vacuum between all components in order to minimise heat transfer. Thermistors embedded within all components and connected to a PCB (printed circuit board) are used to measure the temperature in each component as well as to dissipate electrical power.

A. Experiment

Measurement data were acquired in a 60 MeV clinical proton beam at the CCC (Clatterbridge Cancer Centre) cyclotron [2]. A 4 mm collimator was placed on the nozzle to restrict the beam size. In order to avoid irradiating the thermistors during off axis measurements, a polystyrene mount was constructed which held the calorimeter (and its frame) at a 45 degree angle. A radiograph of the calorimeter at 0 degrees is shown in Fig. 1. The mount itself was placed on an electronically controllable moveable stage, with a distance of ~ 20 cm between the end of the nozzle and the front face of the calorimeter. The temperature in all components of the calorimeter was recorded during and after exposure to on- and off-axis proton beams.

B. Finite element heat transfer simulations

A model of the calorimeter was created in COMSOL Multiphysics® - a finite element analysis solver and simulation package. Accurate dimensional measurements of all the calorimeter components were taken prior to assembly, and these were used in the model. Some simplifications were made, such as omission of the PCB and thermistors. The Clatterbridge proton beam was approximated as a 3 mm radius cylindrical heat source (to account for the divergence and spread of the proton beam) with a depth-dependency based on an unmodulated proton depth dose curve.
TOPAS (TOol for PArticle Simulation) is a Monte Carlo particle transport simulation software based on the GEANT4 toolkit, specialising in the modelling of proton beams. Component dimensions of the Clatterbridge beam line were obtained and a model was built to produce a depth dose curve with bin widths of 0.07 mm and diameter 5.3 mm, corresponding to the diameter of the chamber used for measurements. The TOPAS model beam energy and beam energy spread were tuned to match the experimental data.

III. RESULTS

The temperatures in the various components of the calorimeter were plotted over time and compared to the results from COMSOL, as shown in Figs. 2 and 3. When a component is irradiated its temperature rises, then falls once the beam is turned off.

IV. DISCUSSION

The comparison between the measurements and COMSOL results allowed us to compare the heat flows in each situation. The agreement in the core is very good, with relatively small differences in off-axis irradiations. There are larger differences in the inner jacket (although note the different scale in Fig. 3), although the on-axis measurements agree very well.

These differences may be explained by the differences in the initial heat distribution – the Clatterbridge proton beam is not an idealised cylinder of heat. In order to investigate the impact of this effect, simulations will be run in TOPAS, scoring the dose deposited in each component of the calorimeter. These results will be imported into COMSOL and the simulations re-run as a further refinement of this study.

The agreement between the measured and the TOPAS simulated depth dose curves is very good. This gives us confidence that the simulations described in the previous paragraph will give a close approximation to the actual dose distribution within the calorimeter.

V. CONCLUSION

The development of a primary standard for scanned proton beams is under way. This work will contribute to the characterization of the calorimeter in scanned proton beams, allowing the accurate and traceable calibration of instruments used routinely in clinical proton beams. The Monte Carlo model has been validated for unmodulated beams and is currently being used to create a more accurate heat distribution input for the simulation, thus improving the model and our understanding of the calorimeter.

VI. REFERENCES


[34] A. Wray, Clatterbridge Cancer Centre. Private communication, 2016.


[78] “FEMLAB transforms into COMSOL Multiphysics, which also adds CAD import, and unit systems.” Press Release, September 2005. COMSOL Inc.


