Calorimetry for Proton Therapy: Case For Support

Project Outline

Funding is sought for a 12-month period to develop a plastic scintillator-based calorimeter for use in proton therapy. This is a development of the PVT Optical Modules used for the SuperNEMO calorimeter. This calorimeter is intended for use in a clinical proton therapy facility, with the following uses:

1. To provide the final energy measurement stage for a proton imaging system;
2. To provide fast measurements of the clinical proton beam energy as a part of the daily quality assurance process;
3. To provide improved diagnostic information of the 60 MeV proton beam at the Clatterbridge Cancer Centre ocular proton therapy facility.

A rudimentary system has already been tested successfully, in collaboration with Clatterbridge, providing an estimated energy resolution at 60 MeV of $\sim 1.3\%$ (Appendix C). However, this detector needs to be optimised for use with protons above 300 MeV in order to provide the necessary calorimeter stage for a proton CT system (section 2). It is estimated that this calorimeter would provide an energy resolution below 1% above 100 MeV (Appendix B).

1 Introduction

Of the various modalities employed in modern cancer treatment, surgery, chemotherapy and radiotherapy remain by far the most significant. Of the two non-invasive therapies, radiotherapy is the more targeted: beams of X-rays — usually in the 6–14 MeV range — are delivered to the patient from multiple directions to intersect at the cancer site, maximising the radiation dose deposited in the tumour. First described by Robert Wilson in 1946 [1], proton therapy is a more precise form of radiotherapy that provides significant benefits over conventional X-ray radiotherapy. The energy loss profile of protons and the much smaller beam spot sizes allow a precise tuning of the delivered dose through careful selection of the proton beam energy. This leads to a more effective cancer treatment with fewer incidences of secondary malignancies [2]. This has particular significance in the treatment of deep-lying tumours in the head, neck and central nervous system, particularly for children whose bodies are still developing and are particularly susceptible to long-term radiation damage.

2 Proton Imaging

Compared to conventional radiotherapy, proton therapy is still a developing technology. While the accelerator systems required to provide the 250 MeV proton beams are mature technology, numerous challenges — both clinical and technical — must be overcome before proton therapy has as sound a clinical footing as X-ray radiotherapy [3]. Amongst these challenges, effective imaging is of critical importance.

Traditional treatment planning with photons requires multiple patient CT images to build up an effective diagnostic image for patient planning, both before the start of and during treatment, to allow changes in the tumour volume to be monitored. However, the increased localisation of proton dose delivery requires a corresponding increase in imaging resolution, exposing the limits of traditional CT imaging. In addition, X-ray CT images do not provide information on the proton-specific absorption characteristics of tissue surrounding the treatment volume: a conversion factor must be used in order to convert between CT imaging and proton dose distribution plans. Also, in existing proton therapy centres the patient must be imaged away from the proton delivery nozzle: any resulting movement of the patient's internal anatomy between imaging and proton delivery will negatively impact the treatment quality, since dose distributions are so closely tied to the tissue local to the proton path.

An alternative is to use higher energy protons to image the patient [4]: protons above 300 MeV are used to ensure they emerge from the body without significant dose deposition. Using the same proton beam for both imaging and treatment ensures the patient does not have to be moved between imaging and treatment: in addition, the anatomical information acquired from the imaging does not have to be adjusted from a different imaging modality. As such, imaging with protons is highly desirable for optimum proton therapy treatment. A conceptual proton radiography or tomography system consists of a series of tracking layers upstream and downstream of the patient, with some method of measuring the final energy of the diagnostic protons [5]. Individual proton energy measurements at the 1% level are therefore essential for a proton imaging system. In addition, an accurate calorimeter would also provide valuable quality assurance measurements of the treatment protons.

3 Calorimetry for Proton Therapy

This proposal seeks to adapt existing calorimetry technology for the precise measurement of proton energy in a clinical setting. This technology was developed by the UCL High Energy Physics group for the SuperNEMO experiment looking for an extremely rare nuclear process: neutrinoless double beta decay [6]. Individual Optical Modules (OM) developed for the SuperNEMO calorimeter consist of a PVT scintillator block (ELJEN EJ-200) directly coupled to a high-QE 8" PMT (see Fig. 1): more details are given in Appendix B. EJ-200 has a high light output as well as being extremely fast, with a time constant below 2 ns [7]. Such properties are highly beneficial for the clinical applications outlined above. Such a short time constant provides the possibility for event rates above 10 MHz, some 5 orders of magnitude faster than the sampling calorimeters envisaged for other proton imaging systems such as PRaVDA[1]. Preliminary calculations indicated that such a SuperNEMO detector could achieve an energy resolution in the region of 1% for clinical proton energies, again exceeding the performance of a sampling calorimeter. Early experimental measurements using the 60 MeV clinical proton beam at the Clatterbridge Centre for Oncology corroborate these predictions (see Appendix C).

The primary goal for this detector system is to provide a high-speed, accurate calorimeter for a proton imaging system. The ultimate aim for this calorimeter will be to integrate it into a full proton CT detector, complete with high precision particle tracking: such a detector system is well beyond the scope of this proposal but does provide a clear avenue for future research. In addition, accurate measurements of proton energy will be necessary as part of the quality assurance procedures for a clinical proton therapy centre, such as the one under development at UCLH. Daily QA will be necessary before delivering treatment, part of which will involve confirmation of the proton energy for all clinical energies (70–250 MeV) in addition to the standard dosimetry measurements: fast characterisation of beam energy and energy spread is clearly beneficial. Beyond this, measurements at Clatterbridge have already provided new information on both the energy spread and time structure of the Clatterbridge beam (see Appendix C). It is anticipated that, as part of the detector tests at Clatterbridge, further measurements will be made of the 60 MeV beam to provide a better understanding of the clinical performance and routes for improving and optimising treatment.

Finally, early simulations have indicated that EJ-200 is an effective neutron detector. The clinical effects of neutrons are extremely poorly documented, with the necessity that the neutron flux within the treatment room be as low as possible. As such, measuring both the neutron fluence and spectrum within the treatment room is crucial. It is anticipated that the detector simulations already carried out will be expanded to include neutron effects and optimise the performance of the SuperNEMO calorimeter module for neutron absorption.

[1] medicalphysicsweb.org/cws/article/research/50931

4 Research Plan

In order to develop a calorimeter for proton therapy capable of measuring protons and neutrons with the necessary resolution, the research programme will proceed as follows:

1. **Confirm the detector's ability to measure the Clatterbridge proton beam energy with a resolution of $\sim$1% (FWHM) when the beam is operating at its nominal treatment conditions.** The first test at Clatterbridge (see Appendix C) showed that the detector is capable of measuring the proton beam energy with a resolution of $\sim$1% (FWHM). However the measurements were carried out at the lowest possible proton fluxes with the cyclotron ion source operating at artificially low levels. It is important to ascertain that the detector can reach the same performance at nominal beam running conditions. Pile-up is a particular concern which can bias the resolution measurement. A set of measurements under clinical beam conditions will be carried out using collimators to adjust the beam intensity to fit the detector timing properties.
2. **Develop the equipment capable of investigating the fine time structure of the proton beam. Measure the time structure of the Clatterbridge proton beam.** During the first beam tests there were indications of highly non-uniform timing structure of the proton beam, with clusters of protons arriving within a few tens of ns even with a total proton rate below 1 kHz. While it is possible this was caused by the low current running conditions required for this test, such behaviour must be investigated under clinical conditions, since rapid dose deposition is known to have an effect on cell damage and repair mechanisms. Qualitative studies of this non-uniformity can be done with the existing setup. However to quantify the exact time beam structure an additional detector suite must be built, comprising small and thin plastic scintillators and fast PMTs (either 3", SiPM or multi-anode PMTs).
3. **Calibrate the existing detector at a neutron source at NPL. Investigate modifications to improve the neutron detection efficiency.** To measure neutron backgrounds, calibrating the detector with a certified neutron source will be necessary in order to determine experimentally the detector's efficiency for neutrons of different energies. The detector's ability to do neutron spectroscopy will be characterised, with necessary modifications to the experimental setup to optimise for this measurement. Neutron calibrations will be carried out at the National Physical Laboratory (NPL) in Teddington (see Section 5). In particular NPL's Van de Graaff accelerator complex provides a source of mono-energetic fast neutrons. Sources, such as ^{252}Cf, will also be used to provide a continuum spectrum of fast neutrons.
4. **Measure the neutron background at Clatterbridge.** The neutron flux at proton therapy facilities is poorly known, yet it has to be monitored to avoid its adverse biological effects on the patient. Using calibrations described in (3) measurements of the neutron fluence and energy spectrum at Clatterbridge will be carried out. A brass or aluminium beam stop of a few cm will cut out the protons, allowing measurements of the neutron and gamma background. A pulse shape analysis will provide neutron/gamma discrimination: a Caen DT5751 digitiser used for the previous measurements has the capability to run a dual-gate signal integration through a built-in FPGA, allowing on-the-fly pulse shape analysis. Tuning of the digitiser will enable development of an analysis to optimise the efficiency $\times$ purity product for neutron/gamma discrimination. This will provide an essential tool for neutron background measurement in clinical environments.

All experimental activity described here will be underpinned by extensive MC simulations based on GEANT-4. This will build on the existing simulations carried out for the first Clatterbridge beam test (see Appendix C) and the UCL HEP group's expertise in neutron interaction simulations (C. Ghag, UCL Dark Matter) and beam simulations for accelerator development (Jolly). Test beam data from Clatterbridge and calibration data from NPL will be used to tune the simulations.

5 Project Costs and In-Kind Contributions

Funding is sought at the level of 50k to facilitate a research programme to meet the goals set out in Section 4. This is broadly subdivided as follows:

- £20k for 30% of postdoc time at 80% fEC to carry out the necessary detector simulations and experimental tests;
- £20k for experimental equipment, including modifications to the existing detector and associated data acquisition;
- £5k for ~ 12 days workshop time;
- £5k for travel to/from Clatterbridge and NPL for experimental measurements.

More details are provided in Appendix D. In-kind contributions make up a significant fraction of the support for this project and have already enabled the detector development detailed above and in Appendix C. In late 2013, £10k funding was obtained from UCL Physics that provided 3 months postdoc support and a small amount of equipment and travel: this enabled these measurements to be carried out at Clatterbridge. In addition, 2 days of access was provided by A. Kacperek at Clatterbridge to their 60 MeV clinical beam, with significant technical support provided alongside the facilities access. Similar access is being provided by Clatterbridge for the purposes of this proposal (see accompanying Letter of Support): it is anticipated that 4 trips will be made to Clatterbridge over this 12-month period for the purposes of further beam line tests. Any such collaboration relies heavily on the expertise of those with clinical experience and the input of A. Kacperek and colleagues at Clatterbridge is gratefully acknowledged.

A PhD studentship was secured through the UCL BEAMS Impact scheme, for which NPL is the co-sponsor. This PhD student will work on developing the detector system described in this proposal, including the refinement of the GEANT-4 simulations for protons and neutrons and future clinical measurements. The collaboration with NPL will also provide access to the calibrated neutron source, as well as expertise in proton and neutron dosimetry. A number of trips will be made to NPL in order to measure the performance of the detector in response to neutrons. In addition to the postdoc time included in this proposal and the full-time PhD student, postdoc assistance is being provided free-of-charge by M. Easton, a former PhD student of S. Jolly, at approximately 50% over a 6–12 month period (until he emigrates to China).

6 Track Record of Applicants

Dr. Simon Jolly (Principle Investigator) has 15 years experience as an accelerator physicist. He is a member of the UCLH proton therapy procurement team and the UK Technical Advisory Group, providing accelerator advice to both the UCLH and Christie proton therapy projects. An acknowledged expert on accelerator diagnostics, Dr. Jolly leads the development of the energy spectrometer for the AWAKE plasma wakefield experiment at CERN.

Prof. Ruben Saakyan is co-spokesperson of the SuperNEMO collaboration. He was behind the original development of the SuperNEMO calorimeter and led the R&D that resulted in the construction of SuperNEMO as one of the UK flagship projects in neutrino physics. He has some 20 years experience in detector instrumentation for particle physics including scintillator detectors, photo-detectors, gaseous chambers, liquid noble gas detectors and the associated readout technologies. Saakyan worked closely with industrial partners on the development of photo-detectors (Hamamatsu, ET Enterprises).

Prof. David Waters has worked on experimental collider physics, cosmic-ray physics and neutrino physics. He is currently UK Principal Investigator for the SuperNEMO project, and has extensive experience commissioning detectors in addition to performing simulations and data analysis. He has supervised several PhD students and numerous undergraduate students on a range of topics ranging from detector development and construction through to precision electroweak measurements.

Appendix

A Proton Therapy in the UK

Due to the focus on the traditional cancer treatment modalities, proton beam therapy treatment (PBT) in the UK has lagged behind the remainder of the developed world. The Clatterbridge Cancer Centre (previously the Clatterbridge Centre for Oncology) is the only facility in the UK providing clinical proton therapy treatment. A Scanditronix cyclotron delivers 60 MeV protons for treating a range of ocular tumours [8]. The penetration depth for 60 MeV protons is only 31 mm in water (to isocentre): energetic enough only to penetrate to the back of the eye [9]. For other tumours, specific cases are referred overseas for treatment: somewhere between 50 and 100 patients a year (predominantly paediatric) are sent either to Switzerland or the US [10]. In 2011 the UK government announced funding for 2 full-sized proton therapy centres, to be based at University College Hospital in London and The Christie in Manchester. These will provide treatment for a much wider range of cancers, allowing more patients to be treated closer to home. Procurement for these centres began in 2013, with doors expected to open some time after 2018. Unlike the majority of proton therapy centres worldwide — particularly in the US — the 2 UK centres are publicly funded and the indications list prioritises some of the most challenging cancers, particularly central nervous system (CNS), head and neck and paediatric cases [10]. In addition, the target is to treat 1,500 patients a year, split between both centres, which requires significant improvements in throughput over other full-scale proton therapy centres.

As such, it is expected that a significant research programme will run alongside the clinical facilities, not only to improve the quality of treatment for such difficult cases but also to address the unique challenges present in such a large and complex indications list. In this regard, University College London is in a uniquely strong position. A close relationship already exists between UCL and UCLH in many areas, of which proton therapy is no exception. Prof. Gary Royle of the UCL Medical Physics Department is the PBT Research Lead for UCLH and is the only academic to sit on the executive board for either UCLH or The Christie. In addition, Dr. Simon Jolly of the UCL High Energy Physics group is both a member of the UCLH procurement team and the UK Technical Advisory Group, providing advice to both hospitals on the accelerator procurement. At UCL, a number of well established research programs exist that support proton therapy. Within the Engineering Faculty, the Department of Medical Physics and Bioengineering [2] is one of the largest in the UK, with research expertise in various aspects of radiation physics and detectors. The UCL Centre for Medical Image Computing (CMIC) [3] is at the forefront of research to improve diagnostic imaging in medicine, including x-ray and proton CT for proton therapy. In addition, the High Energy Physics Group has an internationally recognised track record in detector development, with leading roles in the ATLAS, MINOS and SuperNEMO experiments. Finally, the intention to include a research room within the UCLH PBT facility gives UCL a unique opportunity to contribute to proton therapy research and support the particular challenges of PBT treatment at UCLH.

Given the complexity of the UK PBT indications list [10], a number of research areas must be investigated in order to provide the level of service required by the NHS:

1. Throughput optimisation: a combination of patient scheduling, treatment planning and rapid beam switching to meet the particular demands of the UK indications list.

2. In-room imaging: more advanced imaging techniques are required to provide the necessary resolution to match the more precise dose distributions available from protons (see below).

[2] www.ucl.ac.uk/medphys
[3] cmic.cs.ucl.ac.uk

3. Dosimetry: both charged particle and neutron dosimetry must be carried out to verify the treatment plans and accurately measure the dose delivered for each patient, particularly for neutrons where the Relative Biological Effectiveness (RBE) is poorly known.

4. Data management: centralising patient data (including imaging data) from the few hundred referral centres around the UK to one of the two proton therapy centres, then back out again after treatment.

While these research areas are not confined to the UK and are also being pursued by the international hadron therapy community, the unique challenges of the complexity of the UK treatment list adds urgency to the investigation of these areas, particularly in the case of throughput optimisation as other centres will not have had to face the demands of the UK indications list. These are in addition to the other prominent research areas in hadron therapy, the most prominent being: improved, lightweight, compact gantry design; improved understanding of the radiobiology of hadron-tissue interactions and RBE of hadrons as a function of energy; and long-term study of clinical outcomes for hadron therapy. Further information is given in the accompanying "Pathways To Impact" document.

B SuperNEMO Optical Modules

SuperNEMO is a neutrinoless double-beta decay experiment currently under construction at UCL and other laboratories worldwide. It uses a Geiger mode tracker in conjunction with a plastic scintillator calorimeter. The calorimeter has been optimised to measure electrons with energies of $E_e \sim 0.5 - 4$ MeV which is the energy range of interest for neutrinoless double-beta decay.

B.1 Optical Module Development

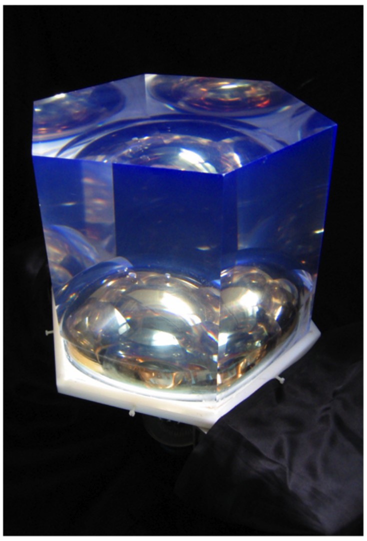

Figure 1: A PVT scintillator block directly coupled to a high-QE 8" PMT. The block is 19.3 cm deep and the minimum thickness of scintillator between the front face and the PMT mounted at the rear is 10 cm. This device was found to have the best resolution for MeV energy electrons.

Prior to construction, an extensive R&D project was undertaken at UCL to improve the calorimeter energy resolution. Different scintillator geometries and compositions as well as PMT configurations were tested. The best result was obtained for a hexagonal PVT scintillator block

(EJ-200 manufactured by ELJEN) directly coupled to a modified high-QE 8" PMT (Hamamatsu). The development of the photo-detector was conducted in a close collaboration with the manufacturer. As a result the quantum efficiency of the photo-cathode was improved, the number of dynode stages changed from 10 to 8 greatly improving the PMT timing properties, and the divider chain was optimised to provide an optimal balance between the collection efficiency and linearity. The resulting product, Hamamatsu R5912-MOD, currently attracts a significant interest from a number of experiments beside SuperNEMO. A picture of the optical module is given in Fig. 1 and further details may be found in [7]. The performance of this device is given in Appendix B.3 below.

B.2 Detector Modelling

The detector response to a pencil proton beam has been simulated using the GEANT-4 simulation tool that models particle interactions with matter. The chemical composition of the scintillator material and the geometry of the setup was described. The scintillator was modelled as a square scintillator block measuring 256 mm x 256 mm x 120 mm. The digitisation package took into account the quenching of the scintillation light in plastic scintillator for protons (Birk's law). The energy deposited in the scintillator was smeared in accordance with the number of photo-electrons (p.e.) generated by unit energy and by assuming that the resolution and its energy dependence is dominated by Poissonian fluctuations in the number of generated photo-electrons. The number of photo-electrons at 1 MeV was taken from test bench data with the optical module exposed to mono-energetic electrons. This test yielded an energy resolution of FWHM (1 MeV) = 7.5% corresponding to 982 p.e. at 1 MeV.

A simple model for the quenching factor for protons is given by Birk's law :

$$\frac{dY}{dx} = \frac{S}{1 + kB\,(dE/dx)} \times dE/dx$$

where dY/dx is the light-yield per unit path length. In [11] a value $kB = 0.207\,\mathrm{mm/MeV}$ is stated to be a good fit to the data. For the purposes of this estimate it is assumed that the quenching factor approaches unity as $dE/dx \to 0$; that is, the light yield for protons is the same as electrons in the limit of low ionisation density. This in effect fixes the constant of proportionality S in the expression above.

B.3 Estimated Energy Resolution

Simulations were carried out for a proton beam of 60 MeV corresponding to the energy of the Clatterbridge beam. Fig. 2 shows the energy deposited by these protons in the scintillator block on the left and the range the protons travel in the scintillator on the right.

One can see from Fig. 2 that due to quenching the visible energy deposited in the scintillator by a 60 MeV proton beam has a Gaussian distribution with a mean of 39.4 MeV. The width of the distribution is $\sigma = 0.225$ MeV corresponding to the energy resolution of FWHM = 1.34%.

Fig. 3 shows the energy deposition versus depth of the scintillator block for incident 60 MeV protons. The Bragg peak is clearly visible with protons ranging out at around 30mm in the scintillator material.

C Previous Experimental Results

Previous measurements were made at Clatterbridge in early December 2013 with a modified version of the SuperNEMO optical module. Since no appropriate DAQ equipment is available at Clatterbridge, extensive use was made of existing equipment within the UCL HEP group: a Caen DT5751 digitiser for data acquisition, a Caen NDT1471 desktop power supply for the

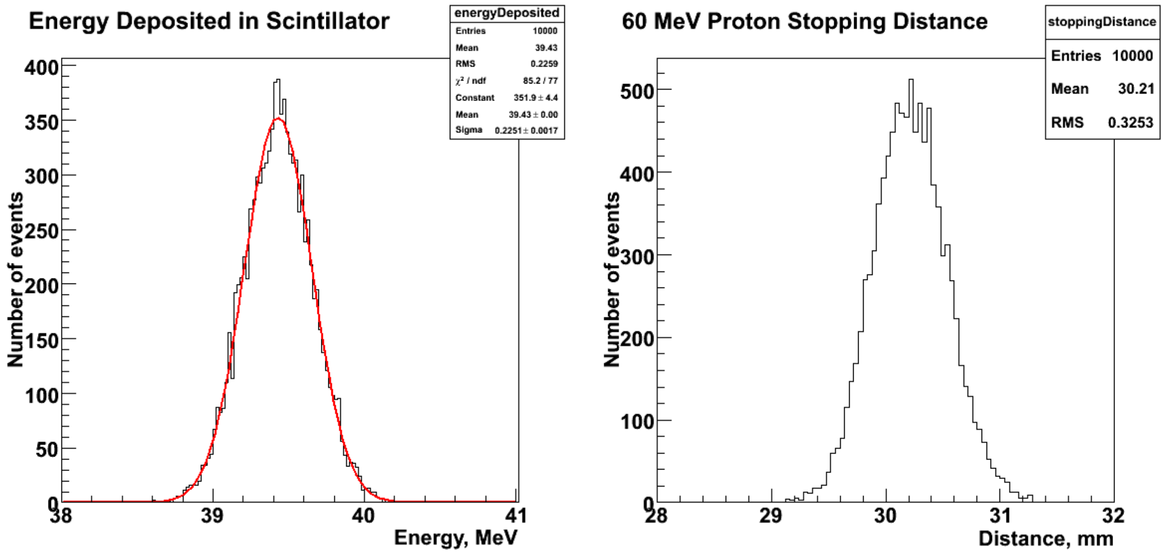

Figure 2: The energy deposited by 60 MeV protons in the scintillator block (left) and the range of the protons in the scintillator block (right).

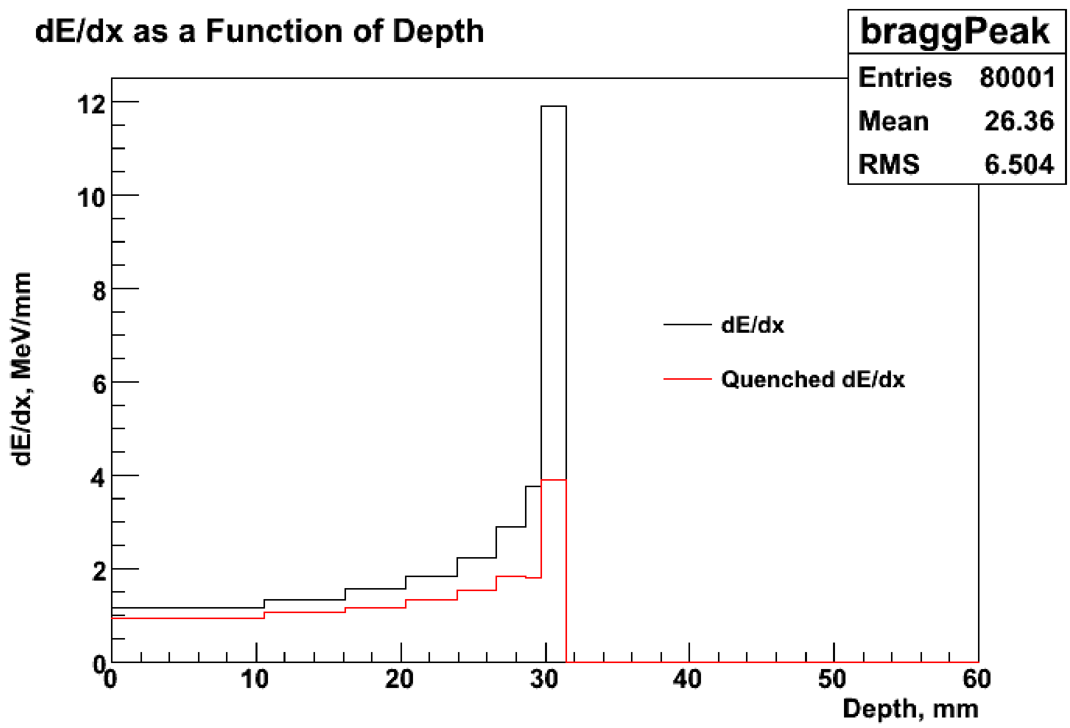

Figure 3: The energy deposition versus depth of the scintillator block for incident 60 MeV protons.

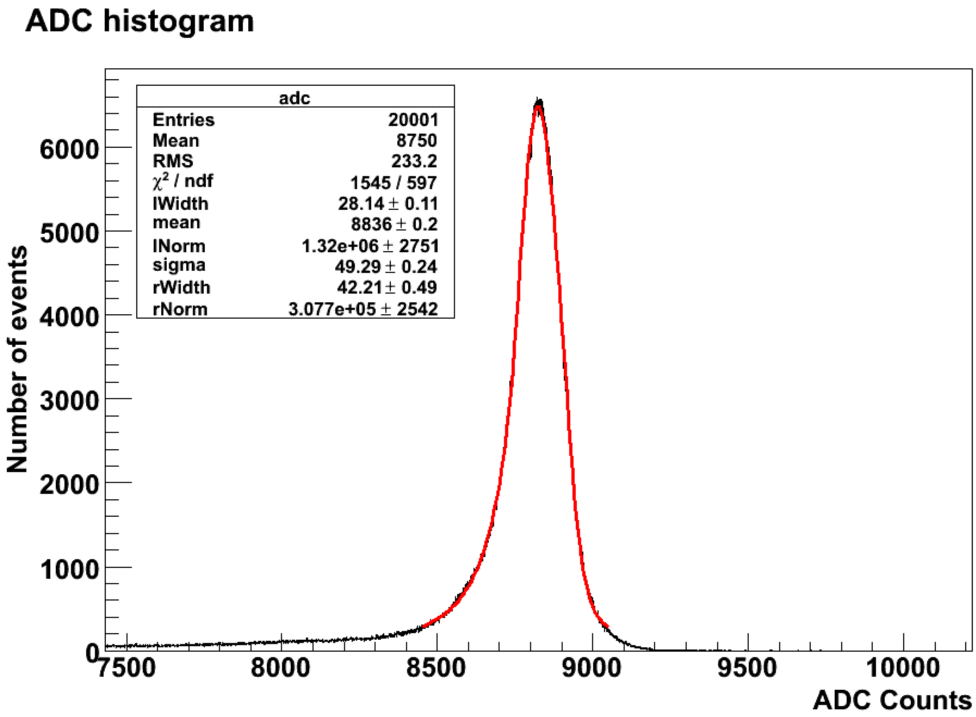

Figure 4: Response of modified SuperNEMO optical module to 60 MeV protons.

PMT and all necessary cabling was brought from UCL. Measurements were made over a 2-day period during which the UCL group were granted exclusive access to the Clatterbridge clinical beam and treatment room. Data was taken with different configurations of the beam, DAQ trigger and PMT HV settings. The proton rate was carefully controlled through the insertion of various collimators into the treatment nozzle (approximately 50 cm upstream of the scintillator block), as well as the adjustment of the ion source gas supply and discharge current and the cyclotron RF phase. The energy of the protons incident on the scintillator block was varied by inserting absorbers of different thicknesses. The analysis of the data has not been completed yet but initial results are extremely promising: the optical module response to 60 MeV protons is shown in Fig. 4. Remarkably, the 1.34% measured resolution is extremely close to the predicted estimate of 1.3% (see Appendix B.3). These results indicate that the detector concept as outlined is sound. However, further developments are required in order to optimise the optical module for use as a calorimeter for clinical protons: these are described in Section 4.

It should be noted that, at higher energies, the resolution improves, assuming that the stated quenching factor holds. The predicted energy resolution of the detector as a function of energy is shown in Fig. 5. These results indicate that the detector can achieve an energy resolution below 1% (FWHM) above proton energies of ~ 100 MeV, provided that the detector linearity regime can be maintained at a $< 5\%$ level.

D Cost Breakdown

As stated in Section 5, 50k of funding is sought to support the research outlined in this proposal. This is broadly apportioned as follows:

- £5k for travel to/from Clatterbridge and NPL for experimental measurements.
- £5k for ~ 12 days workshop time;

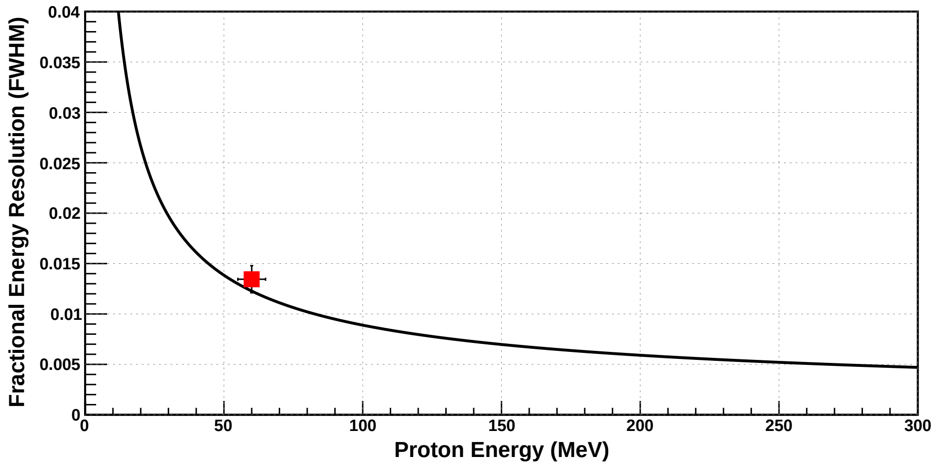

Figure 5: Predicted energy resolution of PVT-based optical module for protons. The red point indicates the measured resolution at 60 MeV.

- £20k for experimental equipment, including modifications to the existing detector and associated data acquisition;
- £20k for 30% of postdoc time at 80% fEC to carry out the necessary detector simulations and experimental tests;

The travel budget largely covers the 4 planned 2-day trips to Clatterbridge, each of which totals $\sim$ £1k, including travel to/from London and 2 nights accommodation for 4 people plus associated equipment transport costs. The remaining £1k is intended to cover the visits to NPL for neutron measurements, including equipment transport costs. £5k is requested for workshop time at UCL to cover the manufacture and assembly of the modified detector geometries. This includes machining of the detector housing and support and additional machining of plastic scintillator blocks should modifications to the stock geometry be necessary.

A proportion of the necessary equipment is already available for use within UCL HEP. A Caen DT5751 digitiser is highly portable and will be used for the experimental MCA to acquire the detector energy spectrum. A Caen NDT1471 desktop power supply is also highly portable and provides the necessary high voltage supply for up to 4 PMTs. The single optical module that provided the results described in Appendix C is available and will be used as the baseline for any modified detector geometries. The £20k equipment costs are subdivided as follows:

- £9.7k for a LeCroy WaveRunner portable oscilloscope. While a number of oscilloscopes are available within UCL HEP and at Clatterbridge, they do not provide the necessary combination of speed, bandwidth, data analysis capability and portability necessary for use in the Clatterbridge control room. Due to the high speed of the EJ-200 scintillator, a high bandwidth oscilloscope is necessary to correctly analyse the signal information: some pulse shape analysis capability is also required. A compact scope is also highly desirable.
- £1.5k for a data acquisition laptop. The DT5751 needs a Linux or Windows-based PC to run the data acquisition: the opportunity for immediate data analysis is also highly desirable.

- £1.5k for 2" or 3" PMTs. A number of large (8" to 12") PMTs are available at UCL from previous experiments — including SuperNEMO calorimeter prototypes — that couple to the large SuperNEMO Optical Module PVT blocks, but it is anticipated that smaller scintillator blocks will be required for a segmented calorimeter for a proton imaging system: this will require PMTs of matched size.
- £1.0k for a set of SiPMs. Non-negligible magnetic fields are present in proton therapy treatment rooms from the proton beamline, particularly those with gantries due to the close proximity of the 135° final dipole. PMTs becoming increasingly susceptible to magnetic fields as they get larger. The use of SiPMs in place of PMTs would eliminate this susceptibility and it is anticipated that PMTs will be replaced with SiPMs for the later experimental tests.
- £3.5k for EJ-200 PVT scintillator blocks. A number of detector geometries will need to be investigated, requiring the purchase and machining of several pieces of PVT scintillator.
- £1.0k for optical fibres, light guides, cement and wrapping to couple the PVT scintillator blocks to the PMTs/SiPMs and provide appropriate light tight shielding.
- £1k for cabling and patch panels. At Clatterbridge sufficient cabling must be provided to run along the 20 m maze between the detector in the treatment room and the DAQ/HV hardware in the control room. It is anticipated that a certain amount of high quality BNC signal and HV cable will be installed into cable trays at Clatterbridge to provide permanent cabling between treatment room and control room without running the cables along the floor of the maze, along with the necessary patch panels.
- £0.8k of miscellaneous costs, including detector support structures.

As mentioned previously, a large amount of manpower is provided as in-kind contributions to the project. The Impact PhD student, who will start at UCL in Autumn 2014, is part-funded by UCL BEAMS with the remainder from NPL. Matthew Easton, a former PhD student with extensive experience in accelerator simulations, is providing at least 6 months of his time at 50% free-of-charge before emigrating to China with his family, since he wishes to gain greater experimental detector experience before leaving the country. Beam time and associated expertise at Clatterbridge is also being provided free-of-charge and constitutes significant clinical input, since experience with clinical protons is not available elsewhere in the UK. Jolly is funded at 50% by the UCL Physics Department to develop novel research programmes relating to proton therapy. Saakyan and Waters are funded under the STFC Consolidated Grant for future detector development.

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