A NOVEL TISSUE EQUIVALENT PHANTOM FOR HADRON THERAPY

Project Overview

This proposal is a collaboration between the Department of Physics at the **University of Liverpool** and the **Clatterbridge Centre for Oncology** (CCO). It aims to demonstrate a “proof of principle” for a high performance phantom for measuring the Bragg peak position in a tissue equivalent medium.

Optimisation of radio or particle-therapy relies on the use of phantoms for simulating the in vivo effect of radiation. These phantoms are generally ion-chamber based phantoms which can determine the Bragg peak profile along the direction of the beam with mm precision and/or solid state diodes that also provide similar resolution in the transverse direction. These technologies are gradually replacing existing, passive, techniques which rely on photographic film. To mimic human tissue surrogate materials are used in front of the active detectors. The surrogate materials can either be liquid, for example water, or solids. Particle beams pass through a known depth of the surrogate material and the energy deposited at a particular depth measured. Sensors can be moved through in a liquid tank to provide longitudinal information or, alternatively, 'solid water' [1] plates can be placed over a matrix array to provide the transverse profile. Solid water plates provide a rather coarse spacing between 'z’-positions and consequently a loss of critical information of the longitudinal beam profile. The cost of water phantoms in standard radiotherapy is typically between 50 to 100 k£.

There are two major manufacturers of phantoms for particle therapy: PTW [2] (Germany) and IBA (Belgium), offering a range of mainly water phantoms. The products of both companies suffer from limitations. PTW provides a rather coarse resolution over the volume typically ~1mm in z and 8 mm in xy and a slow response, as it integrates the dose for a few seconds. IBA has recently tried [3] to overcome some of these limitations, with its Blue Phantom^2 offering, and provides a continuously scannable water phantom; however this retains a fairly coarse 5mm pitch array, and is optimized for electron and photon radio-therapy applications.

For hadron therapy applications a scanning, high resolution phantom with fast response, i.e. with frame readout in the MHz range that can allow for proton counting, promises substantial advantages over existing commercial products. In the long term such a system provides the possibility to integrate the dose deposition information with the real-time beam feedback control system to optimize the beam. We aim to demonstrate the feasibility of building such a phantom to obtain real time response, high O(10μm) spatial accuracy, and excellent energy resolution matched to the clinical needs specified by CCO. The aim is to substantially out-perform currently available instruments in three areas:

- High speed, low-noise real-time readout allowing the possibility of faster scans and control feedback from the phantom.
- High spatial resolution of between 10 to 100 microns in 3D and high energy resolution
- Unparalleled levels of radiation tolerance (operation to $<10^{16}$ p cm^{-2}) ideal for the hadron therapy environment without the need to replace the active element.

To deliver this performance we propose to use silicon detectors originally developed for Particle Physics applications which offer unsurpassed position resolution and speed for detecting charged particles. They are inexpensive, do not require gas supplies and exhibit a well understood and documented hadron radiation tolerance. Furthermore equipped with low cost, extensively tested, and robust electronics our detectors represent a major leap forwards over the commercially utilized Si sensors.

The technique we propose here is a liquid phantom which can be rapidly scanned with a segmented silicon detector to measure the energy deposited by the beam as a function of the depth. The unique ultra fast response of our radiation hard detectors allows individual proton counting; a Bragg peak scan will provide real-time feedback to the operators on the dose to be released by the therapy beam in the target and surrounding tissue. This liquid phantom will make use of a thinned silicon detector to enhance the accuracy of the scan[(1)]. The precision of the reconstructed profiles can be selected to be of the order of tens of micron which is over an order of magnitude finer than that currently available and closely matches the precision needed clinically. The existing ultra low noise electronic readout systems provide fully corrected data (clustered, pedestal subtracted, common mode corrected hits) at over 1MHz to disk, with <0.1 % deadtime. The system could be deployed at any hadron therapy centre either alone or in combination with other existing beam monitoring equipment.

Description of the project

The proof of concept will be built in a few logical stages.

Stage 1: In order to choose the optimum thickness of the sensors for precise measurement of the deposited energy and the ideal liquid, a programme of simulation will be performed at Liverpool. The simulations will build upon the considerable experience with Geant4 in the Physics Department for the development of a Monte-Carlo simulation of a proton beam-line and will incorporate the CCO simulations of passive-scattering systems. The latter resource is currently being implemented on NWGrid for patients receiving advanced photon radiotherapy at CCO. The set of software tools developed for this work will be adapted for the simulation of the phantom filled with various liquids.

Stage 2: To verify the simulation silicon diodes of known thicknesses will be used to profile the Bragg peak in air at the Clatterbridge Centre. The sensors will be read out by a wide bandwidth current amplifier, already in use at Liverpool, that provides the large dynamic range needed for the measurement. This will be coupled to a high performance DAQ system of proven design.

Stage 3: These studies will be repeated in liquid. The option of using liquid implies the use of a thin coating or “dry bag” for isolating the silicon detector operating in the phantom. This is readily possible with silicon detectors and will be engineered at Liverpool

Stage 4: A precision “hand pulled” scanning system will be designed and mounted to allow scanning over 350mm in the longitudinal axis and 120mm in the transverse plane with high position accuracy. In the concept stage the hand driven system, although slow, is cheap and

[(1)] Analysis suggests an advantage in using thin silicon as it minimises systematic uncertainties associated with energy deposition in the silicon itself.

adequate to demonstrate the qualities of the instrument. This will be designed to allow the "plug-in" of a motorized 3D drive system. Attention will be given designing the tank to minimize the turbulence and resistance to detector motion due to the liquid.

Stage 5: The verification of the choice of the liquid for the tissue equivalent phantom will be performed at Clatterbridge. The validation of this technique will be made by clinical experts who will assess the tissue equivalent quality.

Stage 6: The system, equipped with the silicon pad diode of the chosen thickness will be demonstrated in the Clatterbridge proton therapy beam. This simple thinned pad diode in combination with the scanning system will provide an accurate profile of the energy deposited by the therapy beam in the beam-axis direction. This is arguably the most important information because it describes the effect of the hadrons as a function of the penetration depth in the target body.

We believe that stages 1-6 can be completed within 8 months if funded. Thus we also propose additional steps which extend the flexibility and usefulness of this prototype. The remaining 4 months will be used to check the radiation tolerance (robustness) of the system and to prove the full 3-D reconstruction of the deposited energy. Usually the information on the energy deposited in the column of tissue irradiated by the beam is inferred by the beam spot size. To provide the full 3-D reconstruction of the deposited energy we plan to scan the beam with a high resolution segmented detector. The appropriate devices for this purpose are high resolution hybrid silicon detectors coupled to high dynamic range fast readout electronics.

If time permits, we also propose to build a two layer sensing station. The first sensor will still provide the energy information, while the track information (gathered by introducing the second) will be used to validate the 'good signals' coming from beam protons, removing the spurious signals that produce high energy release in the first sensors without producing a track in the detector pair.

Project partners

The Liverpool Department of Physics hosts the JIF financed Liverpool Semiconductor Detector Centre (LSDC) that delivered both the ATLAS EndCap-C array and the LHCb Vertex Locator (VELO) for the CERN Large Hadron Collider (LHC). The former consisted of 988 silicon modules which were mounted, fully characterised and then integrated into a $13m^2$ array prior to shipment to CERN. All 42 LHCb double-sided VELO modules were fully assembled, bonded, tested and delivered by Liverpool to CERN. The n-in-p technology, proposed and pioneered by Liverpool, is the present baseline for the majority of the sensors that will be installed in future detectors at the upgraded LHC.

Liverpool is a major player in silicon detector R&D for high energy physics tracking applications. Liverpool researchers are internationally recognised lead scientists in the development of radiation hard sensors. The PI here is the spokesman of the CERN based 300 member RD50 collaboration which is the leading international collaboration dedicated to radiation tolerant sensors. Collaborators at Liverpool include the spokesman for the ATLAS Upgrade and the current UK VELO project leader.

The clinical proton beam at the Clatterbridge Centre for Oncology, the only one in the UK, will be made available for the duration of this project subject to availability of the proton beam between treatments and simulations. We have agreed that sequences of up to 4 days will be made available. For optimised studies, variable fluence rates can be obtained by operator adjustment, down to maximum dose rates of 100 Gy min^{-1}.

The University of Liverpool will provide the expertise to support the Monte Carlo study of the synthetic phantom material selection.

The mini-IPS scheme is the ideal framework for funding this activity. Individually development of the phantom is beyond the scope of funding, and clinical expertise of Liverpool, and individually beyond the technical capability of CCO. Together, with funding, the groups can integrate state-of-the-art sensors developed in the UK with the expertise from the country's only NHS hadron therapy facility to develop an important enhancement to patient treatment.

Risk assessment

The project combines a set of technologies that are well proven within the expertise of the project partners. We consider this a low risk project. In our view there can be technical issues associated with using the liquid surrogate material as a coolant to the sensor. The University of Liverpool would reduce the potential impact of this by researching alternate cooling strategies.

References

[1] See e.g. http://www.ptw.de/1883.html?&no_cache=1&cId=5497

[2] http://www.cnmcco.com/dosimetry/PDFdocs/slabPhantoms/CNMC_solidwater.pdf

[3] http://www.iba-dosimetry.com/complete-solutions/radiotherapy/relative-dosimetry/blue-phantom-2