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A new silicon tracker for proton imaging and dosimetry

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ABSTRACT

For many years, silicon micro-strip detectors have been successfully used as tracking detectors for particle and nuclear physics experiments. A new application of this technology is to the field of particle therapy where radiotherapy is carried out by use of charged particles such as protons or carbon ions. Such a treatment has been shown to have advantages over standard x-ray radiotherapy and as a result of this, many new centres offering particle therapy are currently under construction around the world today. The Proton Radiotherapy, Verification and Dosimetry Applications (PRaVDA) consortium are developing instrumentation for particle therapy based upon technology from high-energy physics.

The characteristics of a new silicon micro-strip tracker for particle therapy will be presented. The array uses specifically designed, large area sensors with technology choices that follow closely those taken for the ATLAS experiment at the HL-LHC. These detectors will be arranged into four units each with three layers in an x–u–v configuration to be suitable for fast proton tracking with minimal ambiguities.

The sensors will form a tracker capable of tracing the path of ~200 MeV protons entering and exiting a patient allowing a new mode of imaging known as proton computed tomography (pCT). This will aid the accurate delivery of treatment doses and in addition, the tracker will also be used to monitor the beam profile and total dose delivered during the high fluences used for treatment.

We present here details of the design, construction and assembly of one of the four units that will make up the complete tracker along with its characterisation using radiation tests carried out using a ^{90}Sr source in the laboratory and a 60 MeV proton beam at the Clatterbridge Cancer Centre.

1. Introduction

Particle therapy: alongside surgery and chemotherapy, radiotherapy remains one of the three major tools used by clinicians to combat cancer today. Typically, the standard approach for radiotherapy involves the use of x-ray beams, a technique that was first developed for medicine by physicists. Radiotherapy today, still remains a field that continues to go hand in hand with developments in physics and engineering [1]. For cancers deep inside the body or close to critical structures, particle therapy has been shown to have a distinct advantage over standard x-ray radiotherapy. This is a result of the underlying physics that describes how radiation interacts with matter. For charged particles, such as protons, energy loss is described by the well established Bethe–Bloch formula [2] and results in a characteristic 'Bragg Peak'. This is where the majority of the particles stop and where their dE/dx or Linear Energy Transfer (LET) is maximal, resulting in a concentration of the dose in this region. Taking advantage of this dose distribution for radiotherapy was first envisaged by Wilson [3]. For x-rays, energy is lost in an exponential fashion and thus much of the dose is given to healthy tissue before and after the tumour. This can be avoided by using a beam of charged particles such as protons. This sparing of healthy tissue also makes particle therapy the best choice for some childhood cancers, since growing tissues and bones are more radiosensitive than in adults and critical organs are located much closer together. In this case, the excess dose to healthy tissue can cause irreparable damage to developing cells that can cause other cancers later on in life [4]. For this reason, many of the patients that the National Health Service (NHS) in the UK currently sends abroad each year for proton therapy treatment are children [5]. Because of these advantages, approximately 50 centres offering particle therapy

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have been built around the world, with many new centres under construction worldwide including two new NHS proton facilities in the UK.

Proton imaging: instrumental to the planning of any program of radiotherapy is a good imaging modality that can deliver accurate information on the patient's anatomy, and in particular the accurate location of the target volume. For proton therapy, this is carried out by an x-ray CT scan from which the proton stopping power of the tissue can be derived and the necessary range of the treatment beam calculated. During this conversion from x-ray imaging to proton stopping power, an uncertainty in the proton range is introduced, of order 1–3 mm [6]. This arises from variations in density along the proton path [7] and inaccuracies in the excitation energy or electron density value assumed for the tissue [8], as well as from the stopping power conversion method itself [9]. Uncertainties in the proton range increase the amount of dose delivered to the healthy tissue surrounding the cancer and can therefore prevent the treatment of cancers close to critical structures. If this uncertainty could be reduced, several of the limitations with proton therapy could be overcome. These uncertainties could potentially be reduced if the stopping power of the beam could be measured directly i.e. by using protons for imaging as well as for treatment [10]. In order to carry out this technique (referred to as proton computed tomography, or simply *p*CT), a device that can accurately measure the trajectory and energy loss of protons as they pass through an object for many different angular projections is needed [11–14]. The PRaVDA Consortium [15] aims to construct a prototype of the first fully solid state *p*CT scanner using silicon detectors for both the tracking and range (energy) measurements of protons (see Fig. 1) [16–19]. We have designed and begun construction of the silicon strip tracker, using large area ($\sim 10 \times 10$ cm) micro-strip detectors adapted from designs made for the ATLAS experiment at the high-luminosity LHC allowing the sensors to be very radiation hard [20,21]. The sensitive area of the detectors was constrained by the available space on a standard 6-in. silicon wafer and when arranged in the proposed x–u–v configuration provides an imaging area of $\sim$9 cm. Future designs for imaging larger, more clinically relevant areas could be done by using these detectors ganged together (with some dead regions), or by moving the imaging system itself. The current design of the tracker will demonstrate that a completely solid state system offering high-precision directional information on the path of protons can be used in conjunction with an energy-range measurement to perform a *p*CT scan [22].

2. Assembly and readout of the tracking units

Silicon micro-strip sensor: each silicon micro-strip detector has a nominal thickness of 150 μm and is made from n-in-p silicon. The detector contains 2048 strips in total, 1024 read out on each side of the detector by eight ASICs (see Fig. 2). Each strip has a pitch of 90.8 μm and a length of 4.8 cm and its metal layer is capacitively coupled to its implant with a measured coupling capacitance of 122 pF. Further details of the layout and electrical characteristics of the sensor can be found here [22].

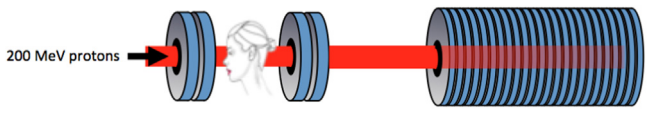

Fig. 1. The PRaVDA *p*CT system concept. The tracker is comprised of the first four units shown here as the two which are placed in front of the object to be imaged and the two after. A range telescope (calorimeter) is placed immediately after the tracker to measure the residual energy of each proton after it has been tracked through the object to be imaged.

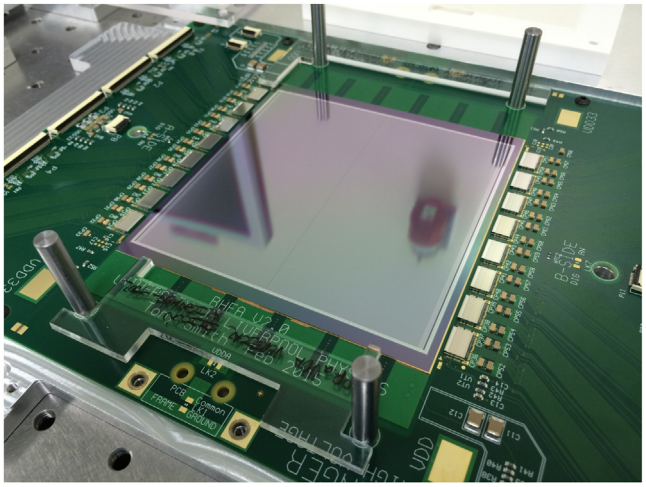

Fig. 2. Alignment of detector to hybrid PCB and aluminium stiffener plate using precision ground tooling consisting of dowels and perspex jigs.

Detectors are aligned to the hybrid PCB and a 12 mm thick aluminium stiffener plate that holds the detector and its associated readout electronics within the tracker unit housing (see Fig. 4). Both the PCB and the aluminium plate contain a square 10×10 cm aperture beneath the sensitive area of the detector to keep the perturbation of the proton path to a minimum. Initial mechanical alignment of the sensors is made using precision ground dowels and a custom built alignment jig with precision ground edges (see Fig. 2) and carried out as part of the gluing and assembly process for each detector used. The alignment achieved with this tooling was found to be within the strip pitch of the detector (90.8 μm) and the rotational alignment to be a few mrad. This was measured using a Smartscope metrology machine which makes optical measurements using a camera in order to estimate the height and flatness and lateral position of the silicon above the PCB surface since the detector could not be probed mechanically due to its fragile nature. Further precision in alignment will be achievable using particle tracks when multiple tracking units are available.

The tracker is comprised of 12 detectors separated into four units each containing three detectors each. Two units are placed either side of the object to be imaged as shown in Fig. 1. Each tracking unit has its detectors held at an angle of 60° with respect to one another in an x–u–v co-ordinate system in order to measure precise x–y locations for particles at high fluence with minimal ambiguities. The angle is achieved by suspending the aluminium plates containing the micro-strip detectors and their associated readout electronics on six precision ground dowels (see Fig. 4).

Readout electronics: the detector is read out by means of an ASIC designed specifically for this application by ISDI Ltd. [23] and known as RHEA (Rapid, High-speed Extended ASIC). RHEA is a binary chip with 128 channels and a bonding pitch of 60 μm fabricated in 0.18 μm CMOS (see Fig. 3). Each channel has two tunable thresholds (DAC1: 2000–10,000 e^-, and DAC2: 20,000 – 160,000 e^-) to allow for high occupancy, and the chip operates at a frequency of 104 MHz and its front-end amplifier with a shaping time of 30 ns. This corresponds to four times the average cyclotron frequency for the energy range of interest (60–200 MeV) at the facilities that will be used. There are two modes that can be used to acquire data: treatment mode and patient imaging or *p*CT mode. In treatment mode all strips are read out at $\sim$100 μs intervals to allow sampling of the beam distribution for quality assurance (QA) purposes and dosimetry during the high fluences used during patient treatment. In *p*CT mode, it is possible to read up to four channels per ASIC with signal over threshold for the expected

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