Nuclear Instruments and Methods in Physics Research A 752 (2014) 42–46

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Sub-aquatic response of a scintillator, fibre optic and silicon photomultiplier based radiation sensor ☆

Sarah F. Jackson [a,*], Stephen D. Monk [a], Steven J. Stanley [b], Kathryn Lennox [b]

[a] Engineering Department, Lancaster University, Lancaster, UK
[b] National Nuclear Laboratory, A709 Springfields, Preston, UK

ARTICLE INFO

Article history:
Received 28 January 2014
Received in revised form
11 March 2014
Accepted 21 March 2014
Available online 29 March 2014

Keywords:
Gamma detector
Dose monitoring
Scintillator
Fibre optic
Linac
SiPM

ABSTRACT

We describe an attempt at the utilisation of two low level light sensors to improve on the design of a dose monitoring system, specifically for underwater applications with consideration for the effects of water attenuation. The gamma radiation 'RadLine®' detector consists of an inorganic scintillating crystal coupled to a fibre optic cable which transports scintillation photons, up to hundreds of metres, to an optical sensor. Analysed here are two contemporary technologies; SensL's MiniSL a silicon photomultiplier (SiPM) and a Sens-Tech photon counting photomultiplier tube (PMT).

A clinical radiotherapy linear accelerator (linac) is implemented as test beam, subjecting the RadLine® to a highly controlled dose rate (ranging from 0 Sv h^{-1} to 320 Sv h^{-1}), averaging at 2 MeV in energy. The RadLine's underwater dose monitoring capabilities are tested with the aid of epoxy resin 'solid water' phantom blocks, used as a substitute for water.

Our results show that the MiniSL SiPM is unsuitable for this application due to extremely high background noise levels, however the Sens-Tech PMT performs satisfactorily and the detected dose rate due to the effects of water attenuation compares strongly with MCNP simulation data and NIST database values. We conclude that the PMT shows promise for its ultimate use in the First Generation Magnox Storage Pond (FGMSP) on the Sellafield site.

1. Introduction

The First Generation Magnox Storage Pond (FGMSP) on the Sellafield site (Seascale, UK) was constructed in the 1950s as an open air pond to receive and store irradiated fuel from Magnox reactors. After a long period of shutdown the fuel started corroding in the pond, which gave rise to increased radiation levels and poor underwater visibility. Over the years the pond has accumulated significant quantities of waste materials, sludges from corroded fuel cladding, fuel fragments and other debris which has blown into the pond, and skips of fuel [1]. As such the government has pledged to spend £7 billion on decommissioning this challenging facility [2]. A system providing real time, reliable and accurate sub-aquatic dose rate monitoring, such as the one proposed here, would assist with current efforts to map these radiation 'hot spots'.

The UK National Nuclear Laboratory's 'RadLine®' is a gamma radiation detector, which consists of a scintillation crystal coupled to a fibre optic cable that transmits scintillation light to a photon counting device. Due to the effects of water attenuation on radiation it is necessary to further develop the RadLine to have greater sensitivity for subaquatic use. In an attempt to improve the design for this type of deployment the currently used charge-coupled device (CCD) is switched with more contemporary technologies; firstly the silicon photomultiplier (SiPM), and later a photon counting photomultiplier tube (PMT).

A clinical radiotherapy linear accelerator (linac) machine is implemented as test beam, subjecting the RadLine to a highly controlled dose rate (ranging from 0 Sv h^{-1} to 320 Sv h^{-1}), averaging at 2 MeV in energy. The RadLine's underwater dose monitoring capabilities are tested with the aid of epoxy resin 'solid water' phantom blocks, used as a substitute for water.

The RadLine detector has several advantages over conventional devices such as Geiger–Müller (GM) counters or Cadmium Zinc Telluride (CZT) devices when performing in aquatic environments. GM and CZT devices perform well over short ranges (<10 m), whereas the RadLine is designed for intermediate (>100 m) to long range (1 km) radiation monitoring. Secondly unlike others

☆This paper was presented at the ANIMMA 2013 conference, and the kind support of The Nuclear Institute to attend ANIMMA 2013 is gratefully recognised.
* Corresponding author.
E-mail addresses: s.f.jackson@lancaster.ac.uk (S.F. Jackson), s.monk@lancaster.ac.uk (S.D. Monk), steven.j.stanley@nnl.co.uk (S.J. Stanley), kathryn.lennox@nnl.co.uk (K. Lennox).

http://dx.doi.org/10.1016/j.nima.2014.03.048

the RadLine's probe does not require power or any electrical input to function and hence it can be safely submerged in water [3].

2. RadLine

RadLine is real time and small and sleek in design, boasting a 4 mm × 4 mm × 40 mm zinc tungstate ($ZnWO_4$) scintillating crystal which produces scintillation light in response to gamma radiation. $ZnWO_4$ possesses the optimum wavelength for fibre optic transmission (between 470 and 540 nm, ideally nearer the red region), does not suffer from afterglow, and its density of 7.62 g cm^{-3} is high enough to attenuate radiation sufficiently. It has an emission spectral range of between 310 and 500 nm, producing 9500 photons/MeV. Here the crystal is connected to a 10 m fibre optic cable, which transmits emission light to a photon detection device (CCD, SiPM or PMT). The number of photons detected is processed by software which measures the dose rate magnitude by means of an initial calibration [4].

The ‘probe’ end of RadLine (crystal and fibre optic cable as shown in Fig. 1) is aluminium encased to provide radiation (above 1000 Sv h^{-1} [5]) and damage resistance during deployment. It is additionally coated with a thin Kevlar ‘jacket’ layer bonded closely to the metal cladding, thus preventing water diffusing into the fibre as this can cause degradation due to the migration of hydrogen ions and the subsequent creation of OH^- groups will absorb transmitted light. This section of the RadLine is electrically inactive which enables it to be used in highly active waste processing and storage areas, as well as low level radiation environments and underwater applications [6].

Fig. 1. The RadLine® probe.

The photon detection device coupled to the optical fibre for the first part of this work is the ‘SensL MiniSL’ SiPM [8] which comprises of an array of avalanche photodiodes where each one operates in Geiger-mode. SiPMs are of great interest in scintillation light detection for gamma spectroscopy, due to their large gain and high speed [7]. Coupling is via SensL's own SiPM fibre coupler option and a FC/PC to SMA mating sleeve over air. The MiniSL consists of a 1 mm^2 detector which is cooled to reduce dark count noise. It also has built in pre-amplification, temperature control and power supply electronics (Fig. 2). Its properties and practical benefits are listed in Table 1.

3. Linac

Linear accelerators (linacs) are devices that use electromagnetic fields to accelerate charged particles to high energies, most commonly used for radiotherapy in cancer patients. The linac produces x-rays by accelerating electrons onto a target which then emits x-rays by Bremsstrahlung. The machine is rated at 6 MeV in energy (also written ‘6 MV’ in medical literature), with a peak of approximately 2 MeV (Fig. 3) [9], the standard pulse rate is 400 Hz, where each pulse lasts between 2 μs and 4 μs. A collimator sets the field size to 10 cm^2, with the surface at the isocenter (100 cm away from the x-ray source). One centimetre thick ‘solid water’ slabs are used to act as an analogue to water; made of epoxy resin these slabs are designed to scatter and attenuate x-rays in the same way as real water [10]. The maximum dose rate is delivered 1.6 cm from the top surface, known as the skin sparing effect; hence the RadLine probe is placed in the centre of the second slab (Fig. 4). The operator then can then precisely control the dose rate (Sv h^{-1}) the RadLine is subject to.

It is recognised that the spectrum of high energy photon radiation from the FGMSP is mostly comprised of a strong Cs-137 peak at 0.662 MeV, as shown in Fig. 3; and this is within the range of the linac, not too far from the modal value.

4. Method

As a high resolution representation of the SiPM's signal is required, an ‘Agilent Technologies Infiniium 8000 Series’ oscilloscope

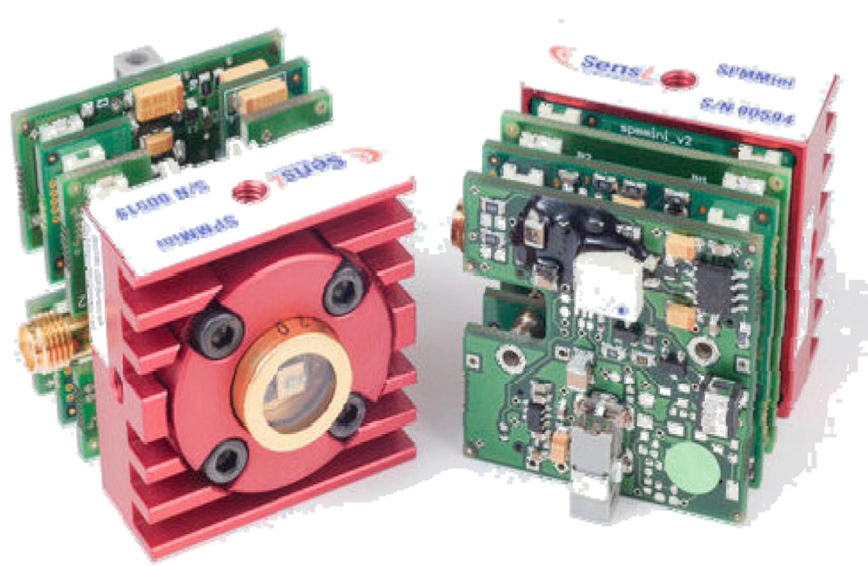

Fig. 2. MiniSL silicon photomultiplier by SensL [8].