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Development of a scintillating optical fiber dosimeter with silicon photomultipliers ☆

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ABSTRACT

A radiation dosimeter for low dose rates based on a scintillating optical fiber coupled to a high gain photon-counting silicon photomultiplier (SiPM) for light readout was developed. The dosimeter satisfies most of the requirements for in-vivo, low dose-rate and real-time dosimetry. The device uses a small scintillator, is flexible and reasonably water-equivalent for photon energies above 100 keV [1,2]. Promising results were obtained when operating the device in current mode, detecting radiation from an X-ray tube in the 15–40 kV range and for anode currents as low as a few μA. As single-photon detectors, the major drawback of SiPMs is their high dark count rate (noise), which is a problem for low dose rate measurements in single photon counting mode. This drawback can be reduced by cooling the SiPMs or by using a much more efficient proposed solution in which two SiPMs operate in coincidence mode reading out the same optical fiber, thus allowing the rejection of false events triggered by dark noise. We have implemented a simple low-cost system, with dedicated front-end electronics operating in pulse mode for coincidence detection. Performance studies of the dosimeter operating in current mode, as a function of the X-ray tube current and voltage, show good sensitivity even for low radiation dose. When operating in pulse mode under low activity gamma irradiation, the coincidence system was able to reduce the dark noise to a residual value.

1. Introduction

Radiotherapy is a standard cancer treatment and can be divided into two major fields: external beam radiotherapy and brachytherapy. With new developments, brachytherapy treatments are growing in number and quality. A critical issue is the monitoring of organs in risk. Radiosensitive organs must be spared to overdoses that can result from inaccurate source placement. Low Dose Rate (LDR)-brachytherapy uses radioactive seeds placed inside the body. While the correct dose must be delivered to the tumor, near healthy tissues and organs must be spared as much as possible. A dosimeter suited for low dose rate measurements would be desirable for LDR-brachytherapy improvement and efficiency assurance and should have the following main requirements: high sensitivity, energy independence and high spatial resolution.

In addition to water-equivalence, plastic scintillators have other interesting properties such as fast decay time (important when operating in pulse mode), good sensitivity, small size and good spatial resolution, dose rate independence and possibility of fast and direct readout [3,4]. Some plastic scintillators have small temperature dependence, as shown by Nowotny in 2009 [5]. More recently, Wootton and Beddar [6] and Buranurak et al. [7] demonstrated that scintillating plastic optical fibers BCF-12 and BCF-60 (Saint-Gobain Crystals, Nemours, France) are not temperature independent. The feasibility of a dosimeter using plastic scintillators for the measurement of the absorbed dose at high dose rates (>12 Gy/hr) and for energies as high as some MeV has been verified elsewhere [1,3,8,9]. With respect to scintillating optical fibers, several authors have previously reported promising results when operating in current mode and under high dose rate [4,10–12] and low energy [13,14].

Within this work, the goal is to evaluate the possibility of using a scintillating optical fiber as detection medium for low dose rate (<2 Gy/hr) and low-energy gamma (<100 keV) dosimetry, seeking in-vivo and real-time operation that is suitable for some brachytherapy applications. This goal is possible due to the high gain provided by the SiPM photosensors used for light readout. Under common irradiation conditions, attention must be paid to light produced in addition to scintillation light in the scintillator and light-guiding fibers. This noise, known as the stem effect, has two possible sources: radioluminescence and Cherenkov light [4].

☆The dosimetric device described in this work is patented (PT106337, Portugal, 2012).

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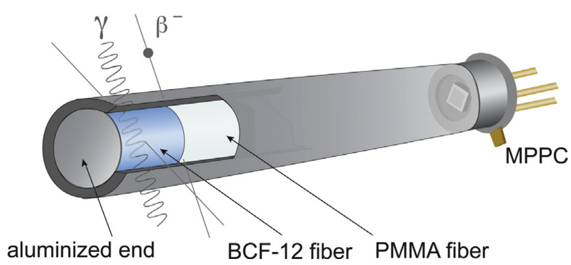

Fig. 1. An artist's illustration of the dosimeter design.

According to Nowotny [15], Poly(methyl methacrylate) (PMMA) fibers are the best option for dosimetry because of their much lower radioluminescence comparing with polystyrene or silica-based fibers. Typical isotopes used in LDR-brachytherapy (Ir-125, Pd-103 and Cs-131) have gamma energies below the threshold for Cherenkov light emission [16,17], so only radioluminescence light is a concern.

2. Dosimeter operating in current mode

2.1. Dosimeter design and setup

As an initial approach, we have developed a simple dosimeter prototype (Fig. 1) consisting of a 10 mm-long polystyrene BCF-12 multi-clad scintillating optical fiber (Saint-Gobain Crystals, Nemours, France) with a diameter of 1 mm, coupled with optical grease to a PMMA clear waveguide fiber Avago HFBR-R (Avago Technologies, San Jose, CA, USA) also with a diameter of 1 mm and length of 10 m that transmits approximately 60% of the initial light [18]. The waveguide fiber was coupled to a Multi-Pixel Photon Counter (MPPC) S10362-11-100U (Hamamatsu Photonics, Hamamatsu City, Shizuoka Pref., Japan), also known as a silicon photomultiplier (SiPM) [19]. The free end of the scintillating fiber was aluminized by thermal evaporation, to increase the amount of collected scintillation light. The scintillating probe and guide fiber were sheathed with a black jacket to isolate them from existing outside light.

Plastic scintillators may present some energy dependency [1,2]. For photon energies above 200 keV, this dependency is weak [20]. Frelin et al. [21] measured the scintillation light yield for several scintillators: in the range between 50 and 200 keV, a decrease of 5–10% in light yield was reported for blue scintillators, although for lower photon energies an increase was observed. For this reason, simple measurements were performed to verify the linearity of the dosimeter for low energy. In this experimental setup, the dosimeter probe was placed in line with the X-ray tube window at a distance of 6 cm and without filtering. Measurements were taken in the accelerating voltage range of 15–40 kV and for anode currents between several tens of μA and 1 mA at room temperature.

2.2. Results and discussion

Fig. 2 presents the MPPC current variation as a function of the anode current. With the increase of the dose rate by increasing the X-ray anode current, a linear dosimeter response is observed for each of the accelerating voltages studied. When the accelerating voltage (V) increases, the slopes of the lines also increase as expected because the tube intensity increases approximately with V^2 [22]. The radioluminescence response of the light guide optical fiber was evaluated by removing the scintillating fiber. The measurements were performed for different tube currents and accelerating voltages and no effect was observed, i.e. no current variation was measured above the 10 nA limit resolution of SiPM bias supply source (Ortec 710, AMETEK, TN, USA).

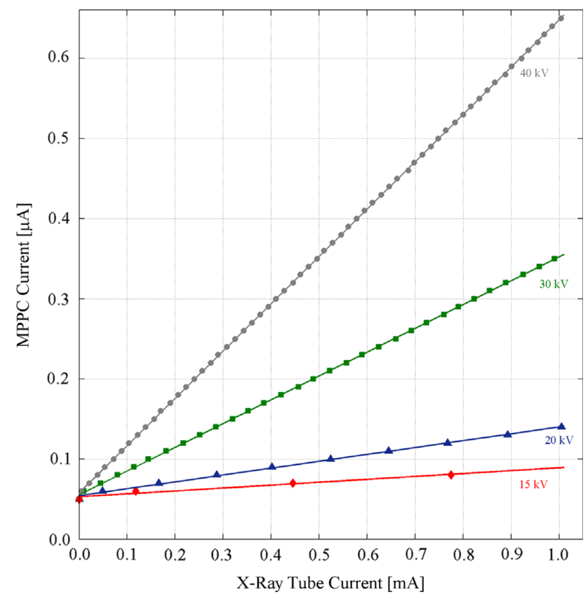

Fig. 2. MPPC current as a function of X-ray tube current for different accelerating voltages.

3. Coincidence mode-operation at low dose rates

3.1. Operation principle and setup

The major drawback of SiPMs is their high dark count rates or thermal noise. The high dark count rate will strongly affect detector sensitivity for low photon energies in low dose rate regimes. Thus, to achieve the desired detector sensitivity and precision, the contribution of thermal noise must be minimized. The typical solution for thermal noise suppression consists in cooling the SiPM some tens of degrees below room temperature. This cooling is usually performed with a Peltier cooler, but this solution increases the complexity and cost of the system and has a residual effect on the reduction of noise, with dark count rates remaining in the 100 kHz range at about 0 °C [23]. In addition, low temperatures introduce water condensation issues. Considering these facts, we hereby propose and evaluate a readout system in which the incoming light is split and detected by two MPPCs operated in coincidence mode (Fig. 3), allowing for a significant reduction of the thermal noise.

In the present concept design, a 1 × 2 optical splitter divides the scintillation light feeding two PMMA fibers that in turn are coupled to the MPPCs. Because commercially available optical splitters are expensive and present high attenuation for visible light, we are developing a 1 × 2 fiber optical splitter. For that reason, in this initial study another configuration was implemented to evaluate the operation principle of the dosimeter in coincidence mode (Fig. 4).

This configuration uses two MPPCs that read the light output at each extremity of a 1.5 m-long BCF-12 single-clad scintillating fiber. A Cs-137 source with an activity of 4.25 μCi and aluminum beta blockage was used. The reference voltage of the comparators was set as low as 0.5 photoelectrons (p.e.). Considering an air-kerma rate constant of 21.77×10^{-18} m^2 Gy Bq^{-1} s^{-1} [24] at 1 mm from the fiber, the air-kerma rate is 3.4 μGy s^{-1}.

For coincidence operation, a dedicated electronics readout system was developed, including a transimpedance amplifier, units