Radiation Physics and Chemistry 81 (2012) 599–608

Contents lists available at SciVerse ScienceDirect

Radiation Physics and Chemistry

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

Characteristics of radiation induced light in optical fibres for portal imaging application

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ARTICLE INFO

Article history:
Received 28 February 2011
Accepted 23 January 2012
Available online 8 February 2012

Keywords:
Cherenkov radiation
Portal imaging

ABSTRACT

The purpose of this paper is to characterize the radiation induced light in optical fibres to optimise the design of a new Cherenkov detector for portal imaging application in radiation therapy. Experiments were performed using a single optical fibre to evaluate the angle dependence, spectrum and temporal properties of the radiation induced light in the optical fibre in comparison with that of Cherenkov radiation. A theoretical model was also developed to compare with experiments. It has been found that radiation-induced light output from the optical fibre under megavoltage (MV) x-ray irradiation is significantly (about 45 times) higher than that under 100 kVp x-ray irradiation for the same dose rate at the fibre. The angular-dependence, spectrum and temporal properties of the radiation induced light in the optical fibre under MV x-ray irradiation match that of Cherenkov radiation. Different angular dependence and spectrum results from that of previous studies on radiation induced light in optical fibres have also been found. The result of the theoretical model agrees with the angle-dependence measurements.

1. Background

Most electronic portal imaging devices (EPIDs) in radiotherapy use a thin Cu plate/phosphor screen to convert x-ray energies into light photons while maintaining a high spatial resolution (Antonuk, 2002). This results in low x-ray absorption (i.e., low quantum efficiency (QE)) of approximately 2–4% for high energy mega-voltage (MV) x rays (Antonuk, 2002; Pang and Rowlands, 2004). A considerable increase in QE for MV x rays is needed for applications, such as MV fluoroscopy and MV cone-beam computed tomography (MV-CBCT) (Pang and Rowlands, 2004; Seppi et al., 2003; Samant and Gopal, 2006a). Furthermore, current EPID systems use high atomic number (high-Z) materials which have an undesirable over-response to low energy x rays when used for dosimetric verification (Pistorius and McCurdy, 2002; Warkentin et al., 2003). Thus, there is a need to develop new EPIDs that have a high QE and use low-Z materials to overcome the obstacles faced by current x-ray imaging technologies (Pang and Rowlands, 2004; Samant and Gopal, 2006a, 2006b; Sawant et al., 2006). A novel detector design was recently proposed (Mei et al., 2006) for a thick high QE detector using a matrix of optical fibres focused towards an x-ray source, as shown in Fig. 1. This detector uses radiation induced light in the optical fibres in the form of Cherenkov radiation as the primary imaging signal (Mei et al., 2006). When MV x rays interact with the optical fibre array, Compton scattering and pair-production processes will produce energetic electrons. Those with sufficient energies in the optical fibres are expected to produce Cherenkov light along their tracks. The light photons produced in the fibre core and emitted within the acceptance angle of the fibre are guided by total internal reflection towards the optically sensitive amorphous silicon (*a*-Si) active matrix flat panel imager (AMFPI) for image readout. The active matrix is made optically sensitive either with an *a*-Si PIN photodiode at every pixel or a continuous layer of amorphous–selenium (*a*-Se). The gap between fibres can be filled with, for example, a black epoxy resin to absorb light which is not guided by the fibres but rather escapes from the sides of the fibres. Preliminary findings (Mei et al., 2006) have shown that such a detector can yield a zero-frequency detective quantum efficiency (DQE) an order of magnitude higher than current low QE EPIDs, while maintaining a spatial resolution comparable to video-based EPIDs (Herman et al., 2001).

An important issue with the design of a Cherenkov detector for portal imaging applications is whether the radiation induced light in the optical fibres is predominantly Cherenkov radiation. This is due to the fact that: (1) there could be other light sources, e.g., fluorescence, in optical fibres; and (2) the design depends strongly on the type or the properties of the light sources in the optical fibres. The purpose of the present work is to characterize

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doi:10.1016/j.radphyschem.2012.01.044

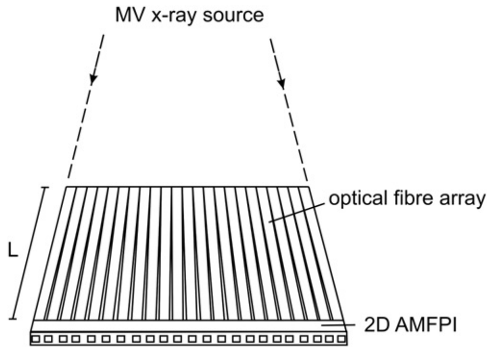

Fig. 1. A cross section of the Cherenkov detector proposed in Mei et al. (2006) with optical fibres focused towards an MV x-ray source. Incident MV x rays interact with the detector and eject Compton electrons within the optical fibre, and these high speed electrons result in Cherenkov radiation. This light is transmitted down the fibre core towards a two-dimensional active matrix flat panel imager (AMFPI) for image readout.

the radiation induced light in optical fibres to optimise the design shown in Fig. 1 and demonstrate that the predominant light source in the optical fibre under MV irradiation is indeed Cherenkov radiation. Although radiation induced light in optical fibres was previously investigated (angular dependence light-output curves and radiation induced light-output spectra were measured with radiation therapy beams for some optical fibres) (Beddar et al., 1992; de Boer et al., 1993; Law et al., 2007; Lambert et al., 2009), all previous studies for radiation therapy applications focused on eliminating the effect of Cherenkov light in, for example, scintillator dosimeters coupled with optical fibres (Letourneau et al., 1999). In contrast, here we want to maximise the use of Cherenkov radiation in optical fibres. In this work, experiments have been performed with the optical fibre used in the Cherenkov prototype in Mei et al. (2006). These experiments were used to evaluate both the contribution of Cherenkov radiation to the total light output, and the angle dependence, spectrum and temporal properties of the radiation induced light in the optical fibre: all of which are crucial for the design of the proposed detector. Discussion on the use of the results of the present study to optimise the design of a high QE Cherenkov detector for portal imaging applications, as well as preliminary results on a prototype array detector are also included.

2. Characteristics of Cherenkov radiation

Cherenkov radiation (or Cherenkov light), discovered by Pavel Cherenkov, is an electromagnetic shock wave of light resulting from a charged particle (e.g., an electron) moving through a dielectric medium at a velocity greater than the speed of light in the dielectric medium (Zrelov, 1970; Jelley, 1958). The speed of light in the dielectric medium is c/n, where c is the speed of light in a vacuum and n is the refractive index of the medium, such that the threshold condition for Cherenkov radiation to be emitted is given by

$$n\beta > 1 \tag{1}$$

where β is the ratio of the particle velocity to the speed of light in a vacuum (v/c). The kinetic energy E_k of the charged particle is given by

$$E_k = \frac{m_0c^2}{\sqrt{1-(v/c)^2}} - m_0c^2 \tag{2}$$

where m_0 is the rest mass of the charged particle. Thus, based on Eqs. (1) and (2) we can determine the threshold energies required to produce Cherenkov radiation in a known medium. For silica ($n=1.46$), the threshold energy for electrons is 191 keV.

Several unique properties of Cherenkov radiation separate it from other sources of light, namely: (1) The spectrum of Cherenkov radiation is broad and continuous: (Zrelov, 1970; Jelley, 1958) it spans the ultraviolet to infrared spectral regions. The relative number of light photons emitted for a given optical wavelength λ varies according to λ^{-2} (the total energy of light photons for a given λ is proportional to λ^{-3}). Thus, its highest intensity is in the blue–violet portion of the spectrum; (2) The radiation emitted has a strong angle dependence: it is only emitted on the surface of a cone at an angle θ_C with respect to the charged particle's trajectory (see Fig. A1 below with $\theta=\theta_C$), where θ_C satisfies the equation:

$$\cos\theta_C = \frac{1}{n\beta} \tag{3}$$

This is in contrast to other sources of light, such as fluorescence, whose light output is expected to be uniform in all directions (Zrelov, 1970; Prasad, 2004). (3) The radiation is created instantaneously with a very short time delay of about 10^{-11} s between the onset of the interaction between the charged particle and the dielectric medium and the creation of Cherenkov radiation. (4) The radiation has a strong dependence on the charged particle's energy: no Cherenkov radiation will be generated below the threshold energy and (5) when the charged particle's energy is above the threshold energy, the total number of light photons generated is proportional to the product of the charged particle's path length in the medium and $\sin^2\theta_C$ (Zrelov, 1970; Jelley, 1958).

In the following we will discuss the experiments to characterize the radiation induced light in optical fibres in comparison with Cherenkov radiation.

3. Materials and methods

3.1. Magnitude of radiation induced light in optical fibres

The purpose of this experiment was to determine the magnitude of light output created in optical fibres under high energy irradiation (MV energy) as compared to that created under low energy irradiation. In all experiments, except for the temporal property measurement, the high energy irradiation refers to the irradiation with either a 6 MeV or 15 MeV electron beam generated from a linear accelerator (LINAC). An electron beam was used instead of a photon beam to simplify analysis and interpretation of the results while characterizing the radiation induced light. This is mainly due to the fact that it is the electrons that generate the Cherenkov radiation. Thus, using an electron beam avoids the additional stage of photons creating recoil electrons in the optical fibre. However, in clinical applications, a MV photon beam is usually used for imaging. The feasibility of using the proposed Cherenkov detector for portal imaging, as well as the angular dependence of radiation-induced light in a single pixel prototype irradiated with a 6 MV beam, have been investigated in Mei et al. (2006) and will be further discussed in Section 5.

The low energy irradiation refers to irradiation with a 100 kVp x-ray beam (since no kV electron source is available) with x-ray energies intentionally chosen below the threshold energy for Cherenkov radiation. Given the strong energy dependence of Cherenkov radiation, it is expected that different magnitudes of light output should be produced between the high energy (i.e, above the threshold energy for Cherenkov radiation) and low energy (below the threshold energy) cases.

The optical fibre used in all experiments was a 10 m long, single fused silica optical fibre (JTFSH, Polymicro Technologies) with a core diameter of 600 μm and coated with a polymer cladding layer to an outer diameter of 630 μm. The fibre core density is 2.2 g/cm^3, with a core refractive index of 1.46 and cladding refractive index of 1.41