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Design of a new tracking device for on-line beam range monitor in carbon therapy

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ABSTRACT

Charged particle therapy is a technique for cancer treatment that exploits hadron beams, mostly protons and carbon ions. A critical issue is the monitoring of the beam range so to check the correct dose deposition to the tumor and surrounding tissues. The design of a new tracking device for beam range real-time monitoring in pencil beam carbon ion therapy is presented. The proposed device tracks secondary charged particles produced by beam interactions in the patient tissue and exploits the correlation of the charged particle emission profile with the spatial dose deposition and the Bragg peak position. The detector, currently under construction, uses the information provided by 12 layers of scintillating fibers followed by a plastic scintillator and a pixelated Lutetium Fine Silicate (LFS) crystal calorimeter. An algorithm to account and correct for emission profile distortion due to charged secondaries absorption inside the patient tissue is also proposed. Finally detector reconstruction efficiency for charged particle emission profile is evaluated using a Monte Carlo simulation considering a quasi-realistic case of a non-homogenous phantom.

1. Introduction

Proton and carbon ion beams are presently used for the treatment of selected solid cancers [1,2]. In comparison with standard X-rays treatments the main advantage of this technique is the capability of delivering a highly conformed dose distribution in the tumor region minimizing the damage to surrounding healthy tissues and possible organs at risk. This is due to the typical dose release pattern of charged particles in the patient tissue which exhibits a large increase of the energy release at the end of the beam range, the Bragg peak. On the contrary X-ray dose deposition, after an initial rise in a few cm below the skin, exponentially decreases with penetration in the tissue. Particle therapy treatments are mainly performed with proton beams, but the use of carbon beams has recently started in Europe and in Japan. Due to its unprecedented dose release accuracy, new dose monitoring devices are needed to fully exploit particle therapy capabilities to deliver the dose in the planned target volume [3,4]. Currently no beam monitors are used to control the dose release in clinical practice while some attempts of using PET scans just after the treatment are reported in literature (for a review see [5]). In the design of a monitoring device for particle therapy, it must be taken into account that the beam is completely absorbed by the patient tissue. On the other hand hadronic beams experience several inelastic nuclear collisions in their path inside the patient and

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these interactions may result in partial fragmentation or in a complete disintegration of both projectile and target nuclei. In this process secondary radiation of different kinds is created that can eventually escape the patient and be used for monitoring purposes.

In particular prompt photons within the 1–10 MeV energy range, emitted in nuclear de-excitations on a few ns timescale, are produced both in protons and in ion treatments. It has already been shown that in proton therapy the Bragg peak can be correlated with the emission pattern of secondary prompt photons [6–8] and first clinical tests of a slit camera exploiting the prompt photons for monitoring purpose are ongoing [9]. No similar device seems to be ready for the clinical use with carbon beams.

Hoverer, as far as carbon beam treatment is concerned, it has been demonstrated that the longitudinal distribution of the emission point of the charged secondaries can be correlated with the Bragg Peak position [10,11]. Furthermore, fast nucleons and nuclear fragments produced in the fragmentation of the ^{12}C beam are emitted mostly in the forward direction, in a time window of few nanoseconds, and may have kinetic energies that exceed a hundred MeV. Such a fragments production is a way far more abundant for carbon beams with respect to proton beams.

Protons and neutrons are the most abundant component produced by fragmentation, and a sizeable fraction of the protons, in particular, has such a kinetic energy that can escape from the patient and then be detected with high efficiency by tracking detectors. This feature of carbon therapy can be exploited for range monitoring, as proposed in [12] where the method of the Interaction Vertex Imaging (IVI) technique (i.e. the reconstruction of the intersection point of two trajectories assumed to be straight lines: namely the primary beam carbon trajectory and the secondary charged particle one) is proposed [13].

In this paper we propose a new device, currently under construction, that is designed to measure with high efficiency the charged particle (proton dominated) emission profile in carbon treatments. We also show a reconstruction procedure that takes into account the absorption of the secondary proton in the patient tissue. The filtering of this "matter effect" allows the device to reconstruct the proton emission profile as at the emission, also in case of realistic non-homogenous phantoms.

The proposed detector, "profiler" in what follows, is part of the INSIDE (INnovative Solutions for In-beam DosimEtry in hadron therapy) project [14,15], a multimodal in-beam dose monitor which includes, beside the profiler, also a PET detector and it is designed to operate at CNAO [16]. The PET detector is described in [17].

The paper is organized as follows: Section 2 describes the detector, Section 3 describes the simulation, the event reconstruction algorithms and a method to determine the Bragg peak after correcting the emission profile for attenuation in the patient. Section 4 reports the expected detector performances and results of the proposed method applied to a non homogeneous phantom case. Section 5 discusses the results and the prospects and Section 6 presents the conclusions.

2. The detector design

The detector is composed of 6 planes of orthogonally placed scintillating fiber layers followed by a plastic scintillator layer and a small calorimeter made of LFS (Lutetium Fine Silicate) crystals. Fig. 1 shows a scheme and a picture of the detector; the principle of reconstruction for a proton is also shown.

The final design is a compromise between compactness, important due to the space limitations in a treatment room, and large geometrical acceptance, which increases the reconstruction efficiency. The amount of material is minimized in order to contain the multiple Coulomb scattering of tracks that could limit track angular resolution. In order to optimize the charged particle detection the choice of the angle of the detector axis with respect to the beam direction is crucial. At narrow angles there is the advantage that the emission flux is enhanced and the charged particle energy is higher (thus the multiple scattering is minimized). On the other hand, due to the projection on the beam line, the spatial resolution on the emission shape worsens and for angles different from 90° the detected emission shape is convoluted with the transverse beam spot size projected on the beam line. In this paper we consider mostly the 90° case.

2.1. The tracker

The tracker is composed of six planes each made of two orthogonally placed scintillating fiber layers (384 fibers each) to provide bi-dimensional view.

We adopt scintillating fibers having a square cross section of $500 \times 500\ \mu m^2$ (multi-cladding BCF-12 from Saint-Gobain) with the minimal plane separation (2 cm). This value is a trade off: enough space is necessary to accommodate the front-end electronics readout and to increase the geometrical acceptance, but at the same time the detector should be as compact as possible. The choice of the fiber size is the result of an optimization aiming to balance signal amplitude and the total amount of material to be crossed by charged particles.

The fibers readout is performed by means of 1 mm^2 Silicon Photomultipliers (SiPM) coupled to the fibers on both the sides; in total the sensitive area per layer is $19.2 \times 19.2\ cm^2$, read by 192 channels. The SiPM are readout by BASIC32_ADC ASIC [18], a custom integrated circuit. The system is designed to sustain a rate of

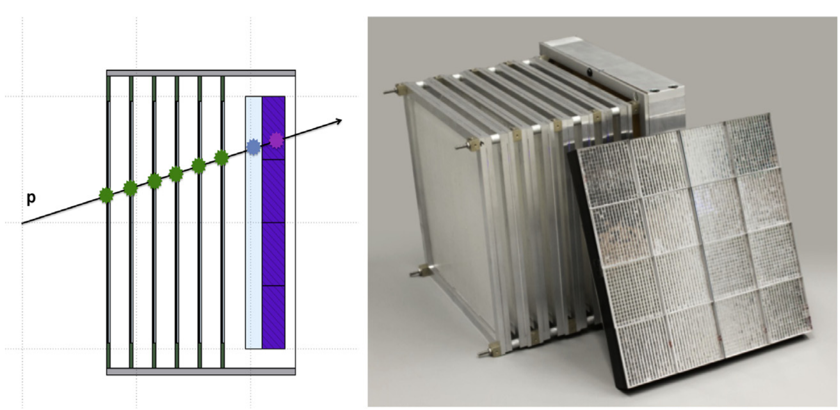

Fig. 1. Scheme of the detector and detection principle for a proton (left). The six tracking planes (dark lines), the plastic scintillator (light blue) and the LFS calorimeter (violet) are visible. A picture of the detector in the assembling phase (right).

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