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Development and characterization of a 2D scintillation detector for quality assurance in scanned carbon ion beams

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ABSTRACT

At the Centro Nazionale di Adroterapia Oncologica (CNAO Foundation), a two-dimensional high resolution scintillating dosimetry system has been developed and tested for daily Quality Assurance measurements (QA) in carbon ion radiotherapy with active scanning technique, for both single pencil beams and scanned fields produced by a synchrotron accelerator.

The detector consists of a thin plane organic scintillator (25×25 cm^2, 2 mm thick) coupled with a high spatial resolution CCD camera (0.25 mm) in a light-tight box.

A dedicated Labview software was developed for image acquisition triggered with the beam extraction, data post-processing and analysis. The scintillator system was preliminary characterized in terms of short-term reproducibility (found to be within $\pm 0.5\%$), linearity with the number of particles (linear fit $\chi^2 = 0.996$) and dependence on particle flux (measured to be $< 1.5\%$).

The detector was then tested for single beam spot measurements (Full Width at Half Maximum and position) and for 6×6 cm^2 reference scanned field (determination of homogeneity) for carbon ions with energy from 115 MeV/u up to 400 MeV/u. No major differences in the investigated beam parameters measured with scintillator system and the radiochromic EBT3 reference films were observed. The system allows therefore real-time monitoring of the carbon ion beam relevant parameters, with a significant daily time saving with respect to films currently used.

The results of this study show the suitability of the scintillation detector for daily QA in a carbon ion facility with an active beam delivery system.

1. Introduction

Hadrontherapy with active scanning technique is a relatively novel treatment modality [1–4] producing highly conformal dose distribution to the target volume by means of protons or carbon ion pencil beams, while sparing the healthy tissues and adjacent organs at risk. The number of hadrontherapy facilities, in particular for the treatment of radio-resistant solid tumors, is rapidly growing worldwide [5]; the Centro Nazionale di Adroterapia Oncologia (CNAO), where this study has been performed, is one of them.

CNAO, the first hospital-based hadrontherapy facility built in Italy, has been active in Pavia since 2011, when the first patients were treated with protons [6], while one year later (November 2012) the clinical activity started with carbon ions also.

It is equipped with four fixed beam lines (3 horizontal and 1 vertical) feeding three treatment rooms and can deliver protons (energy range between 62.73 MeV and 228.57 MeV) and carbon ions (energy range between 115.23 MeV/u and 398.84 MeV/u).

Particles are accelerated by a synchrotron and delivered through a fully 3D active pencil beam delivery modality (active energy variation and transversal beam scanning by magnets).

The set of energies allows steps of 2 mm in water along the longitudinal direction, covering up to 270 mm (for carbon ions) and 320 mm (for protons) in depth. A maximum beam flux of 3×10^9 protons/s and 5×10^7 carbon ions/s can be delivered [7].

Due to the technical complexity of active scanning, the beam characteristics have to be carefully investigated in order to be able to deliver a safe treatment to the patients [8]. In particular, at

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CNAO the main beam characteristics are continuously monitored during treatment delivery by a redundant Dose Delivery System (DDS), consisting of five parallel-plate ionization chambers (two large area chambers, two strip chambers and one pixel chamber) placed in the nozzle [7] of each beam line.

Quality assurance (QA) checks of carbon ion beam scanning irradiation system considerably differ from those of conventional radiotherapy beams [4,9]. In particular, radiographic [10] and radiochromic films are widely used in daily QA as reference detectors for measurements of the single pencil beam (spot size in terms of FWHM, spot position) and for the determination of the homogeneity across the scanned field [11]. Despite the advantage of their high spatial resolution, up to 0.2 mm, radiochromic films are quite expensive, very time consuming and do not provide immediate results (off-line detectors).

Alternative detectors to EBT3 films, such as the IBA Lynx scintillation system (IBA Dosimetry GmbH, Schwarzenbruck, Germany) [12], GEM (Gaseous Electron Multipliers) detectors [13,14] and flat panel detectors [15], have been proposed and used for both therapeutic proton and carbon ion beams.

This paper investigates the suitability of a thin 2D plastic scintillator coupled to a CCD camera (Charged Coupled Device) as an alternative detector to EBT3 films for daily QA checks for particle beams.

Plastic scintillation detectors (PSD) have been widely used in nuclear physics experiments and have gained interest also in photon, electron and proton relative dosimetry [16,17]. They have many advantages over other detectors in small field dosimetry due to their high spatial resolution, excellent water-equivalence in terms of electron density and instantaneous readout. Moreover, PSDs are reliable, robust, cheap and easy to fabricate in the desired shape [18].

The CCD-scintillator system can provide *online* high-resolution 2D readout for measurements on both pencil beams and scanned fields in hadrontherapy [18,19]. With this detector is then possible to perform fast data analysis immediately at the end of each acquisition, a huge advantage with respect to EBT3 films that need to be scanned and analyzed after the measurements. For the first time, at CNAO facility the use of a PSD in QA of carbon ion beams was investigated. The detector performances were evaluated by using newly implemented automatic evaluation routines; the experimental results were compared to the corresponding provided by currently used EBT3 radiochromic films.

2. Materials and methods

2.1. Beam characteristics

Irradiations were performed at CNAO, using the carbon ion pencil beams extracted from the synchrotron and transported along one of the available horizontal fixed beam lines.

Specific details regarding technological aspects on the CNAO beams and the applied dosimetric and QA procedures can be found in [6,8,20–23].

2.2. System components

The scintillator system consists of a thin EJ212 (Scionix, Bunnik, The Netherland) plastic scintillator sheet (250 mm × 250 mm × 2 mm), coupled with a 12-bit Peltier-cooled CCD camera through a first-surface reflectivity optical mirror (250 mm × 340 mm × 2 mm).

Table 1
Physical characteristics of EJ212 scintillator [26] compared with EBT3 films main features [27]. The scintillator is made of polyvinyl-toluene (PVT 97%) and organic flours (3%); the material is almost water equivalent in terms of electron density and atomic composition and the high conversion efficiency in light emission makes this scintillator very attractive for applications in relative dosimetry.

EJ212 Scintillator	
Light output, % anthracene	65
Wavelength of max. emission, nm	423
Rise time, ns	0.9
Decay time, ns	2.4
Pulse width, FWHM, ns	2.7
Z_{eff}/A_{eff}	0.5414
No. of electrons per cm^3, $\times 10^{23}$	3.33
Density, g/cc	1.023
EBT3 films	
Wide dose range	1 cGy to >40 Gy
Uniformity in dose	$> \pm 3\%$
Active layer thickness, μm	26–28
Matte polyester layer thickness, μm	100
Total thickness, μm	230

2.2.1. Scintillator

The EJ212 scintillator was chosen as radiation detector for our purpose, representing the best compromise between a suitable light yield and a good response homogeneity, almost equivalent to radiochromic EBT3 films [24,25]. Table 1 summarizes the main physical properties of this scintillator and EBT3 films.

The thickness of the scintillator sheet was chosen taking into account both the expected sensitivity from previous studies performed using proton beams [24] and the need of reducing the radiation scattering effect as much as possible.

2.2.2. Optical mirror

The plane optical mirror avoids the double reflection phenomenon occurring in common commercial mirrors, in which the incident light crosses a 5 mm thick glass layer before hitting the optical surface (made of aluminum and quartz protection) which partly reflects it. The final effect would have been double-image phenomenon, particularly visible for carbon ions due to their small spot size (FWHM <1 cm) with respect to the proton spot size (FWHM up to 2–3 cm).

2.2.3. CCD camera

We used a 12 bit Hamamatsu IEEE1394 Digital CCD Camera C8484-03G (Hamamatsu Photonics K.K., Hamamatsu City, Japan), with a 2/3 size sensor; the CCD has 1344 × 1024 (unbinned) pixels, corresponding to a cell size of 6.45 μm × 6.45 μm and an effective sensitive area of 8.67 mm × 6.6 mm. To reduce the low-dark current originating by thermal electronic noise, the CCD camera is cooled down to -10 °C through a Peltier element. The sensor scans all pixels at a rate of 8.9 Hz [28].

The images can be captured with an integration time ranging from 10 μs to 10 s and an external-triggered acquisition is possible. The CCD camera has a maximum detection efficiency for wavelengths from 500 nm to 600 nm, with a relative sensitivity dropping to 80% at 423 nm.

The readout system includes a Chassis NI PXI-1042, a CPU NI PXI-8108 and an FPGA NI PXI-7811R (National Instruments, Austin, TX, USA).

2.3. System assembly

A schematic view of the whole prototype system is shown in Fig. 1. The plastic scintillator is placed at the isocenter, with its surface perpendicular to the beam direction (Fig. 2); behind the scintillator, at a distance of 20 cm, the 45° optical mirror reflects