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Dosimetric characterization of a silicon diode detector in cyclotron-based passively scattered and synchrotron-based scanning clinical proton beams

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ABSTRACT

A PR60020 silicon diode detector (PTW-Freiburg, Germany) was tested at INFN-LNS cyclotron on the scattered proton beamline (62 MeV) dedicated to ocular treatments. For the first time, the detector was also characterized in scanning proton beams accelerated by the CNAO synchrotron (63–229 MeV).

The characteristics of the diode detector for proton beam dosimetry were investigated in terms of response stability, linearity with dose and dependence on dose rate and beam quality. Depth–ionization curves were measured for unmodulated, unmodulated range-shifted beams and spread-out Bragg peaks (SOBP); results were compared with reference ones obtained with an ionization chamber. Output Factors of narrow beams used in ocular proton-therapy were measured and compared to those achieved using EBT3 films. The PR60020 diode showed a reproducible response as for short-term precision (0.5%) and medium-term stability (1.5%). Dose and dose rate dependence measurements showed deviations from linearity within ±1%. The calibration factor (Gy/nC) was constant within ±1% over the range of proton beam qualities of ocular proton-therapy, while 1.4% maximum variation of diode sensitivity among CNAO energies was found. Output factors agreed with reference ones within 2% down to 5 mm collimator diameter. Bragg peak curves closely matched those acquired with ionization chamber, relative differences being lower than 3% in peak-to-plateau ratios. Very good results were also found for SOBP dose measurements as in scattered and scanned proton beams. In conclusion, diode detector appeared suitable for relative dosimetry and absorbed dose determination in passively scattered and scanning clinical proton beams, particularly for very small fields used for ocular treatments.

1. Introduction

Proton beam radiotherapy is highly effective in treating complex-shape tumors thanks to its highly conformal dose deposition and achievable steep dose gradients [1]. The main advantage of proton-therapy over conventional photon radiotherapy is represented by reduced radiation exposure to nearby healthy tissue and organs at risk [2,3]. On the other hand, proton beams are similar to photon beams in terms of radiobiology, their relative biological effectiveness (RBE) being 1.1, although the need of RBE modeling in proton treatment planning is nowadays a matter of strong discussion in the scientific community [4,5]. This is due to the linear energy transfer (LET) increase in the distal fall-off region of the Bragg peak.

Concerning dose delivery modality, passively scattered beams tend to be replaced in the modern clinical practice by the more efficient pencil beam scanning technique, however they still represent the standard scenario for beam lines dedicated to ocular treatments [6,7].

By a dosimetric point of view, high spatial resolution and small size detectors, with a response linear with dose and a negligible LET and dose rate dependence, are required for accurate proton dosimetry. In particular, small field dosimetry for eye proton-therapy poses additional demands on the detectors to be used. All detectors used for proton dosimetry have some degree of energy and LET dependence, being minimal or even negligible for ionization chambers. As for both scattered and scanned proton beams, parallel-plate ion chambers are therefore recommended as reference detectors for measurement of depth dose distributions in proton beams [8,9]. However, if the field size is smaller than twice the diameter of the cavity of the parallel-plate chamber, then a detector with a better spatial resolution (e.g. mini-chamber, diode or diamond) is recommended [8]. For off-axis

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measurements, radiochromic film is generally assumed as the reference detector [9–15], however pin-point chambers with a radius not greater than 1 mm may be used. Several solid state detectors, such as silicon diodes, thermoluminescence detectors, MOSFET or diamond detectors, widely used for conventional radiotherapy, may represent interesting tools in proton beam dosimetry too [16–28]. However, the suitability of such detectors for proton beam dosimetry should be verified by test comparisons with reference detectors [8,9]. Silicon diode detectors were found to be a suitable choice for high resolution proton dosimetry due to their relatively small size and high sensitivity, especially for use with small fields and high dose gradients as in eye proton therapy and proton radiosurgery [28,29]. Among the different types of silicon diode detectors, only the highly doped p-type (Hi-p) ones have been found to be suitable for depth-dose measurements, because the signals of the Hi-p silicon diode detectors in proton beams are proportional to ionization in all regions of the Bragg curve [19,29,30].

In this work, the dosimetric properties of a commercial p-type silicon diode have been evaluated in a proton beam line dedicated to the treatment of ocular diseases (62 MeV), as well as, for the first time, in high-energy scanning clinical proton beams (63–229 MeV), in particular in terms of dose and dose-rate dependence, response stability, energy and LET dependence.

2. Material and methods

2.1. Diode detector

The PR60020 detector (PTW, Freiburg, Germany) is a p-type waterproof silicon diode detector designed for dosimetry in high-energy proton beams [29,31]. The detector sensitive volume (0.02 mm^3) is disk-shaped with a cross-sectional circular area of 1 mm^2 and a thickness of 20 μm. The sensitive volume is embedded in a waterproof cylindrical housing, 7 mm in external diameter and 45 mm long. The diode has green marks for detector alignment with respect to the beam. According to manufacturer's specifications, the effective point of measurement is located on detector axis, 0.77 mm from detector tip, corresponding to a water-equivalent depth (WED) of the active area of 1.33 mm. In all cases, the diode detector was operated in photovoltaic mode, i.e. with no external bias voltage applied. A leakage current less than 20 fA was measured at room temperature. Unless otherwise specified, all measurements were performed with diode detector axis parallel to beam axis (axial orientation, Fig. 1a).

3. Proton beam lines

3.1. CATANA

A horizontal proton beam line called CATANA, fully dedicated to the treatment of ocular diseases like uveal melanoma, is operational at the Istituto Nazionale di Fisica Nucleare–Laboratori Nazionali del Sud (INFN-LNS) since 2003 [32,33]. About 400 patients have been treated so far. A 62 MeV proton beam accelerated by a superconducting cyclotron is passively shaped for treating ocular diseases with a maximum penetration in water of 30 mm, a 90%–10% distal fall-off less than 0.8 mm and a 80%–20% lateral penumbra of 1.2 mm. The proton beam delivery system is passive, consisting of two high-Z scattering foils for spreading the proton beam to clinical field sizes, a library of range shifters to set the penetration of the proton beam at the desired depth, and a set of plastic modulator wheels to spread the Bragg peak in depth over the tumor thickness in the direction of the beam. Full technological and clinical details about CATANA can be found elsewhere [33–36]. CATANA beamline has been fully simulated with Geant4 Monte Carlo code [36].

According to the IAEA TRS-398 Code of practice [8], a parallel-plate PTW 23343 Markus ion chamber (MK-IC) was used for absorbed dose to water determination under reference conditions (beam monitor calibration). A PTW 34045 Advanced Markus chamber (AMK-IC) was also used as reference detector for depth–ionization measurements of both unmodulated and modulated proton beams. The choice of AMK-IC is related to the small electrode spacing (1 mm) and high electrical field (4000 Vcm^{-1}), the latter providing a collection efficiency close to 1 up to 100 Gy/min in the superconducting cyclotron continuous beam.

A PTW Unidos-webline electrometer was used for all charge and current measurements with ion chambers and diode. A dedicated eye-line custom made water phantom was used for dosimetry measurements. The phantom consists of a PMMA cubic tank (20 × 20 × 20 cm^3), with a PMMA circular entrance window 80 mm in diameter and 0.65 mm thick, through which proton beam was incident. The phantom is provided of a computer-controlled motorized system, with a scanning resolution along proton beam axis up to 0.1 mm. A custom software, developed at INFN-LNS, controls data acquisition and provides data analysis. The minimum water-equivalent depths achievable in the water phantom were 2.1 mm for the diode detector and 1.8 mm for the MK-IC and AMK-IC, corresponding to the sum of the water-equivalent thicknesses of all material layers in front of the effective point of measurement of the detectors. A depth-scaling factor of 0.974 [8] was used to convert depths in PMMA to equivalent depths in water. The calculated WED of both detectors were accounted for in computerized automatic scanning/positioning system. Unless otherwise specified, a 25 mm diameter circular collimator was used for measurements, stated as the reference collimator. Finally, a system based on lasers was used to align the detector on beam axis and provide isocenter identification, placed 83 mm far from final collimator.

Output factors (OFs) in narrow proton beams were measured with diode, MK-IC and EBT3 radiochromic films (Ashland Advanced Materials, NJ, USA) [13,15,28,35].

3.2. CNAO

One out of the three fixed horizontal beamlines available at the Italian National Center for Oncological Hadrontherapy (CNAO) located in Pavia was used for detector characterization. At the hospital-based CNAO facility, both proton and carbon ion beams can be extracted from the synchrotron using the full 3-D active modality (transversal pencil beam scanning and active beam energy selection). In particular, 161 discrete energies are available for protons, in the range 62.7 to 228.6 MeV (i.e. Bragg peak depth in water from 30 to 320 mm). The proton pencil beam spot size in air at the isocenter (in terms of full width at half maximum, FWHM) varies between about 7 mm (for the higher energies) and 22 mm (for the lower energies). Beam can be magnetically scanned over a maximum area of 20×20 cm^2 at the isocenter.

So far, more than one thousand patients have been treated at CNAO since 2011, mainly for skull-base, head and neck, abdominal and pelvic radioresistant tumors. Full technological, dosimetric and clinical details about the CNAO facility are reported elsewhere [37–40].

4. Measurement details

4.1. CATANA

Dosimetric characteristics of the PR60020 diode were investigated at CATANA facility in terms of short and medium term response stability, linearity with dose and dose rate dependence. Measurements were carried-out in the 62 MeV full-energy unmodulated proton beam at the minimum WED of the diode detector in the water phantom (d_0). Linearity with dose measurement was performed in the 0.3–30 Gy range. Five independent charge measurements were recorded for the same nominal delivered dose. Dose-rate dependence was investigated by varying proton beam current in the clinical range (1–7 nA), corresponding to dose rates at isocenter from 10 to 65 Gy/min. The diode current from PTW electrometer and the associated proton beam current from the first