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Towards a compact experimental setup for gas-based microdosimetry

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Abstract. Microdosimetry measures the stochastics of imparted energy at the micrometre scale, and is a reliable experimental technique to monitor complex radiation fields such as those used in hadron therapy. At the Legnaro National Laboratories of INFN, miniaturized gas-based microdosimeters were developed specifically for this kind of applications. However, their use outside research facilities has been hindered by the encumbrance of the gas-flow system which is used to preserve gas purity and of the high-resolution analog electronic chain. To overcome this drawback, a new detector designed to work without gas flow was developed recently. The stability and reproducibility of its response in sealed conditions were studied in two measuring shifts one year apart from each other, both with the analog electronic chain and with a compact digital acquisition system. Preliminary results confirm the possibility to operate the detector with a very compact experimental setup, which could be a major advantage in clinical facilities.

1. Introduction

Hadron therapy is a radiation therapy technique that uses charged hadrons (mainly protons and carbon ions) to treat deep-seated tumours that are located close to critical organs. The advantage of this technique is related to the more favourable physical and biological properties of ions over photon or electron beams. However, nuclear interactions of charged hadrons in matter produce a complex mixed radiation field, with a non-uniform biological effectiveness along the penetrating depth. In radiobiology and in clinical practice, the "quality" of the radiation beam is generally assessed by means of the Linear Energy Transfer (LET), and, for a mixed field, its dose-weighted mean value LET_D. The relation of the biological effectiveness with LET is largely unique [1], even if a dependence on particle type was recognized in literature [2, 3].

A reliable way to monitor complex radiation fields is microdosimetry, which measures the stochastic fluctuations of the imparted energy in a sensitive volume of micrometric size. The reference measuring devices are the Tissue-Equivalent Proportional Counters (TEPCs), gas detectors working in the proportional regime where both the filling gas and the cathode walls have a chemical composition as similar as possible to that of the human tissue [4]. At the Legnaro National Laboratories of INFN,

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miniaturized TEPCs were developed to cope with the very high fluence rates of hadron therapy beams [5]. It has been shown that these detectors are reliable LET monitors, both for protons and carbon-ion fields [6, 7]. They generally work in gas-flow mode in order to ensure the time stability of the chemical composition of the counting gas. However, the encumbrance of the vacuum and gas-flowing system as well as of the high-resolution analog electronic chain that is used for data acquisition prevents a widespread use of mini-TEPCs outside research facilities. For these reasons, a new mini-TEPC designed to work in sealed mode was developed recently [7], to address the need for a compact system suitable for a clinical facility. In this paper, the time stability of the new sealed mini-TEPC is evaluated, as well as the suitability of a compact commercial acquisition system for its operation in a clinical proton beam.

2. Materials and methods

The mini-TEPC used in this work has a cylindrical sensitive volumes 0.9 mm in diameter and height. The cathode is a cylindrical shell with a thickness of 350 μm, made of A150 tissue-equivalent plastic, surrounded by a Rexolite insulator and a titanium external shield, with a thickness of 350 μm and 200 μm, respectively. The water-equivalent thickness of the detector walls is 1.37 mm, if the average stopping power ratios of protons in the different materials is taken into account [7]. The anode is a gold-plated tungsten wire with a diameter of 10 μm.

After a proper cleaning and outgassing procedure, the detector was filled with pure propane at a pressure of 45.4 kPa and disconnected from the vacuum system. In these conditions, the equivalent site size at unit density is 0.75 μm in propane and 0.85 μm in water, if the corresponding ratio of stopping powers is considered [7]. Measurements were taken with the sealed detector at the clinical beam line of CATANA (INFN Southern National Laboratories, Catania, Italy), in a spread-out Bragg peak obtained by passive modulation of a pristine 62-MeV proton beam. The beam fluence was uniform on a circular area 2.5 cm in diameter, and the detector was aligned to its centre. PMMA layers were used in order to degrade the primary beam and perform measurements at different depths.

Two measurement shifts were carried out one year apart, without refilling the detector with new gas. The propane pressure inside the sensitive volume was constant within 1%. The same modulator wheel was used, but a 0.5-MeV difference in the energy of the pristine beam was present between the two shifts. In the first measurement campaign, the signal from the detector preamplifier was fed into a high-resolution analog electronic chain, composed of three spectroscopy amplifiers and peak-sensing ADCs. In the second, a commercial compact acquisition module based on flash-ADCs and digital signal processing algorithms was used in parallel to the analog one, in order to compare the performance of the two systems.

The detector was irradiated with a total dose of about 500 Gy in each experimental campaign. Microdosimetric spectra were taken at 23 different positions in the first shift and at 19 depths in the second, using different stacks of PMMA layers. The energy calibration of the measured spectra was carried out by means of the proton-edge, which corresponds to the maximum energy deposit released by low-energy protons crossing the sensitive volume of the mini-TEPC, following the procedure described in [8]. The position of the inflection point was chosen as the proton-edge marker, and it was assigned a value of 143 keV/μm in water, as discussed in [7]. The proton-edge position was determined separately for each set of measurements, in the last spectrum before the beam is stopped completely, at a depth of 30.9 mm. The same calibration factor was then used for all spectra of the set.

3. Results

Figure 1 shows the comparison of spectra measured with the analog electronic chain one year apart, at water-equivalent depths of 1.4 mm, 25.8 mm and 30.9 mm, corresponding to three representative positions along the SOPB (entrance, mid-SOBP and dose fall-off). As expected, the spectra shift to higher lineal energy with increasing depth, due to the higher energy deposits produced by slower protons. The agreement of the spectra is very good, despite the small differences in beam energy and the position uncertainty (which is about 0.15 mm). This is confirmed also by spectra measured at other depths along the SOBP, even if the positions at which measurements were taken varies slightly, due to

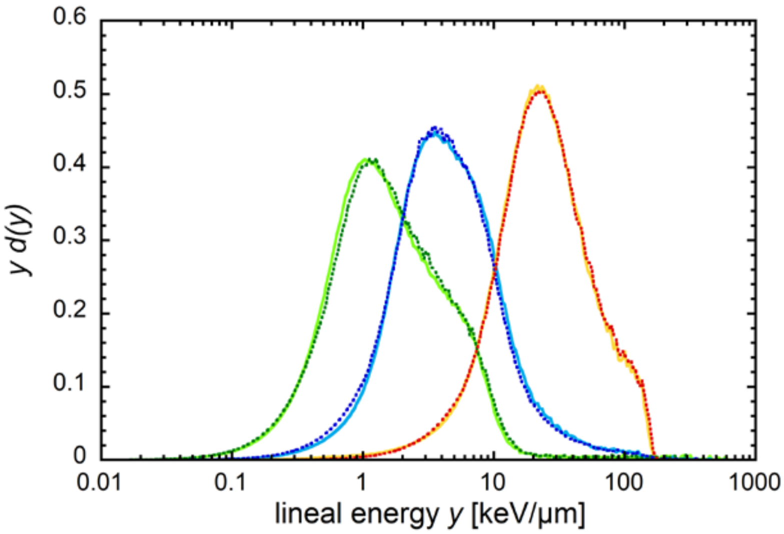

Figure 1. Comparison of microdosimetric spectra taken during the first measurement campaign (full lines) and after one year (dotted lines), at the entrance (green), mid-SOBP (blue) and dose fall-off (orange).

the different stacks of PMMA that were used. This proves the stability of the sealed detector even after one year, despite the very high total dose with which it was irradiated.

The comparison of the spectra measured in the second shift with the analog and the digital acquisition systems is shown in figure 2, for the same depths of figure 1. It was found that the compact acquisition module can sustain a counting rate of about 30 kHz, thanks to a pile-up rejection algorithm that allows to obtain non-deformed spectra for a dead time up to 80%. This maximum counting rate is enough for mini-TEPC operation, since an increasing deformation of microdosimetric spectra for counting rates higher than 30 kHz was observed also with an analog acquisition system [9]. Despite the higher noise level of the digital system and the consequently higher acquisition threshold, linear extrapolation of the low-energy part of the measured spectra allows to recover the entire microdosimetric information, also at the entrance of the SOBP.

To analyse quantitatively the results obtained, figure 3 shows the values of the dose-mean lineal energy measured along the SOBP in the two measuring shifts, taken with the analog electronic chain in the first and with the digital system in the second. The agreement is generally quite good all along the SOBP, within the experimental estimated uncertainty of 5% [7]. As already observed, the y_D values

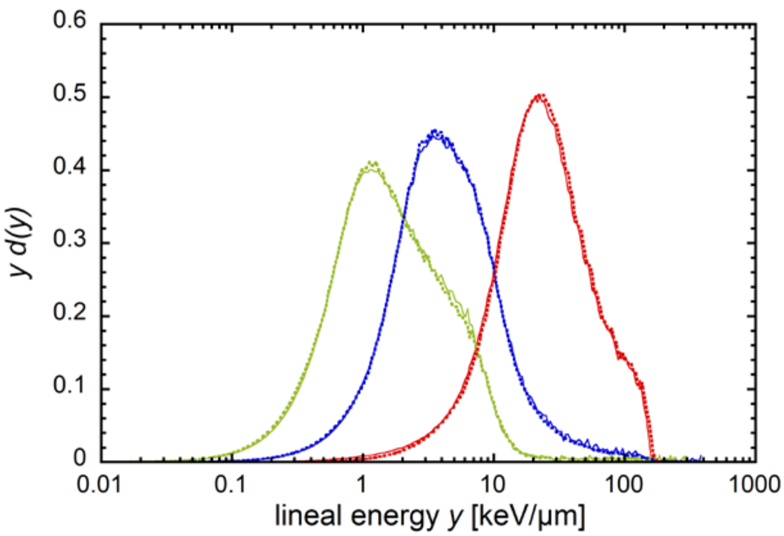

Figure 2. Comparison of microdosimetric spectra taken with the analog electronic chain (dotted lines) and with the digital system (thin full lines), at the entrance (green), mid-SOBP (blue) and dose fall-off (orange).

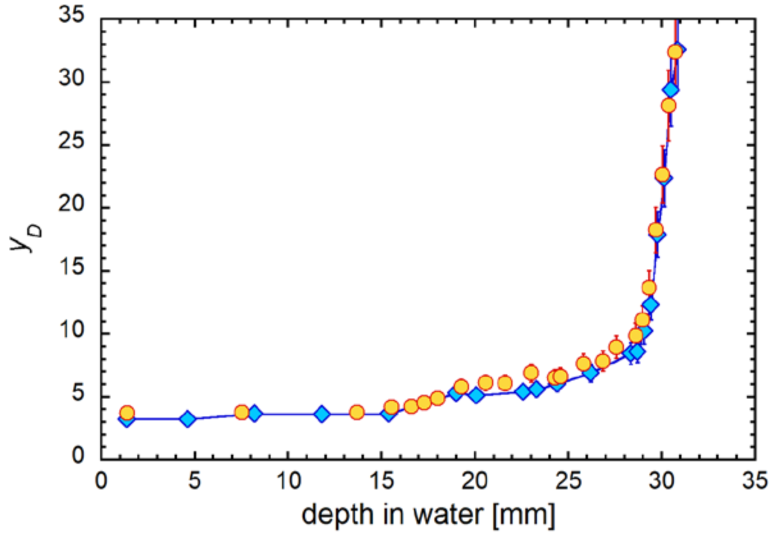

Figure 3. Dose-mean lineal energy y_D measured in the first measurement campaign (blue diamonds and line) and one year later (orange circles), as a function of the equivalent depth in water.

present a sharp increase at the distal-edge of the Bragg peak [7], which reflects the drastic change in beam quality at the end of its range.

4. Conclusions

Despite the small differences in the experimental conditions, the comparison of microdosimetric spectra taken in two measuring shifts one year apart from each other confirms the stability and reproducibility of the detector response in sealed conditions, also after being irradiated with a total dose of about 1kGy. In spite of the higher acquisition threshold, the performance of a commercial compact acquisition system is comparable to that of the analog electronic chain previously used up to a counting rate of 30 kHz. This study should however be repeated in higher-energy proton beams, where the higher threshold could hide a significant part of the spectra at the entrance of the SOBP. However, these preliminary results confirm the possibility to operate a sealed mini-TEPC with a very compact experimental setup, which could be a major advantage in clinical settings.

5. Acknowledgments

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