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Preliminary results of the Gas Electron Multiplier (GEM) as real-time beam monitor in hadron therapy

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ABSTRACT

The use of proton and carbon ion beams in cancer therapy (also known as hadron therapy) is progressively growing worldwide due to their improved dose distributions, sparing of healthy tissues and (for carbon ions) increased radiobiological effectiveness especially for radio-resistant tumours. Strict Quality Assurance (QA) protocols need to be followed for guaranteeing the clinical beam specifications. The aim of this study was to assess the performance of a gaseous detector based on the Gas Electron Multiplier (GEM) technology for measuring the beam spot dimensions and the homogeneity of the scanned irradiation field, which are daily QA tasks commonly performed using radiochromic films. Measurements performed at the National Centre for Oncological Hadron Therapy (CNAO) in Pavia (Italy) showed that the detector is able to monitor the 2D beam image on-line with a pad granularity of 2 mm and a response proportional to the number of delivered particles. The dose homogeneity was measured with low deviation from the results obtained with radiochromic films.

1. Introduction

The National Centre for Oncological Hadron Therapy (*Centro Nazionale di Adroterapia Oncologica*, CNAO) located in Pavia (Italy) uses a synchrotron to deliver clinical proton and carbon ion scanning beams with energy up to 250 MeV and 400 MeV/u (4.8 GeV total energy), respectively [1], with beam spot size in the nominal range of 4–10 mm at the Full Width at Half Maximum (FWHM). The synchrotron can deliver the beam to three treatment rooms (four fixed beam lines in overall) in several spills of ~1 s duration each.

Dose delivery in depth (z direction) is modulated by varying the extracted beam energy (iso-energetic slice or layer), while a pair of magnets scan the pencil beam transversally (*x*-y directions) across the target volume. A redundant and complex Dose Delivery System (DDS) is used for real-time beam monitoring [2]. It consists of five beam monitors placed at the end of each beam line: two parallel plate ionization chambers measuring the beam fluence, two strip chambers for the beam position (one horizontal and one vertical) and one pixel ionization chamber for the beam size and position. Both strip and pixel detectors also provide beam fluence measurements.

Two QA procedures were addressed in this study, namely the measurement of the pencil beam transversal dose profile and the uncertainty in the dose delivered by x-y beam scanning [3]. At CNAO, both the FWHM of the individual pencil beams and the dose homogeneity for scanned fields are typically measured with radiochromic films [4,5]. This type of procedure is relatively expensive, annual cost of 20000 euros, time consuming and does not provide information in real-time.

In this work a triple GEM detector [6] with excellent radiation hardness [7] was tested as a real-time beam monitor, with the aim of measuring both the individual pencil beam dose profiles and the scanned field dose homogeneity.

2. Experimental set up

The triple GEM consists of three insulating kapton foils 50 μm thick, clad on both sides with thin metal layers (5 μm) and located between two electrodes, a cathode and an anode, creating four gaps inside the detector: a drift gap, two transfer gaps and an induction gap (see Fig. 1a). The foils are perforated with a large number of holes, having an external diameter of 70 μm, internal diameter of 50 μm and a pitch of 140 μm. These holes act as multiplication channels for electrons released by ionizing radiation in the gas mixture. If a suitable voltage is applied to the foils, a strong electric field is generated inside

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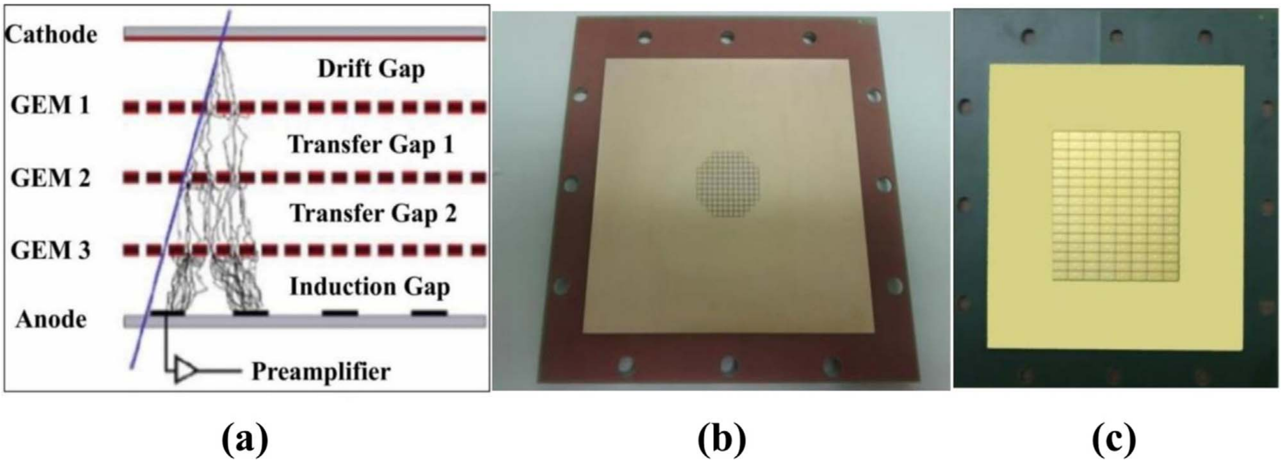

Fig. 1. (a) The triple GEM detector (b) Configuration of 2×2 mm^2 size in a circular area of 3×3 cm^2 (c) Pad read-out configuration: 3×6 mm^2 size organized in a square area of 5×5 cm^2.

the holes, so that electrons can acquire enough energy to develop an avalanche. The electron signal is induced on a padded anode, yielding counts in the corresponding pad area (see Fig. 1b and c). Two triple GEM detectors were built and tested, the read-out of which is shown in Fig. 1b and c:

- GEM1: 2×2 mm^2 pad size, organized in a circular active area of 3×3 cm^2 for beam spot and FWHM measurements
- GEM2: 3×6 mm^2 pad size, organized in a square active area 5×5 cm^2 for the beam scanning procedure

The multiplication gain follows the law $G{\sim}e^{\Sigma V_{GEM_i}}$, with V_{GEM_i} being the voltages applied to each foil, and depends on the gas used: the device employed in this study consists of three foils, with the gain ranging from 10^2 to 10^4 with a gas mixture of Ar-CO_2 70–30%. With increasing gain the electron cloud grows in size, leading to increasing cluster size. Thus the charge is collected from more than one pad and the cluster size can be measured from the mean pad multiplicity by applying a time gate short enough to record only one particle. At a fixed ΣV_{GEM_i} it is advisable to apply a higher voltage to the first foil in order to avoid discharge effects in the induction gap: the optimal configuration of the GEM voltages is $V_{GEM_1} >> V_{GEM_2} \geq V_{GEM_3}$.Due to the large number of holes, the GEM detector can work with high flux of particles (up to 10^8 cm^{-2} s^{-1}) [7], ensuring a linear response over a large dynamic range, as required for use in hadron therapy.

The voltage is applied by a HVGEM NIM module [8]; the values of fields, high voltages and currents are instantaneously monitored. A set of eight CARIOCA-GEM CHIPs [9] shape and digitize the signals induced on the 128 pads of the anode. The sensitivity of the pads is not perfectly uniform and thus a threshold equalization needs to be performed in order to eliminate systematic counting errors [10]. A FPGA motherboard collects the signals from the pads, counting them in several time windows. A multi-slice method was employed during this work, dividing the spill duration into a series of successive time slices without dead time between them independent of the particle rate; the dead time was eliminated by saving the slice data only after the end of the spill [11]. By means of a Labview® program the user can visualize the 2D beam spot online, at the same time recording the number of particles integrated over a selected time sequence.

The detectors were placed on a tripod at a distance of 20 cm ± 2 cm from the DDS (see Fig. 2a), in one of the horizontal beam lines. The motherboard was detached from the detector via a 3 m shielded flat cable connection to prevent malfunctioning that can occur when the FPGA chips are directly exposed to the beam [12]. Radiochromic films were positioned in front of the GEM window in order to compare the beam profiles measured by the two techniques.

3. Detector characterization and acquisition method

The GEM1 (2×2 mm^2 pads) was first characterized using a 252 MeV/u stationary pencil carbon beam of 10 mm nominal FWHM and 5×10^6 particles per beam spot. The total voltage applied to the foils was chosen as 960 V, corresponding to gain 1500. The reason for choosing a low gain is because of the relatively high particle flux, in order to lower the efficiency of the detector and avoid discharge and saturation effects [12]. In principle a double GEM could also be employed, but discharge phenomena are fewer if the same gain is shared between three foils rather than two. The pad multiplicity of single events at 960 V was measured to be 1.1.

The FPGA board used for the GEM data acquisition can record the time dependent integral of the counts for each pad acquired during a spill using the multi-slice method [11]. The beam intensity was measured with slices of 100 ms each; the evolution of the total number of counts per slice as a function of time is shown in Fig. 2b with 9×10^6 s^{-1} being the maximum rate measured.

In addition, the acquisition system shows the 2D count distribution in real time during the X-Y scan of a dose field. A screenshot of the Labview console employing GEM1 detector is shown in Fig. 3 (left), where three panels are shown. In panel A the horizontal and vertical profiles of the count distribution on the pads are shown, accumulated over the entire scan. In panel B the time histogram is visible, showing the total number of counts over the 128 pads per time gate. In panel C the count distribution after the complete scan is shown: the colour denotes the number of counts acquired by the corresponding pad. A single beam spot during the treatment is shown in Fig. 3 (right).

4. Response comparison with the beam monitors (DDS)

The count response of GEM1 was investigated for increasing fluence of the stationary carbon ion beam and compared to the response of the vertical (*x*-axis) strip chamber (SC), which is part of the CNAO DDS [2]. The SC segmented anode is composed of thin aluminium strips 1.6 mm wide with a pitch of 1.7 mm, for a total active area of 21×21 cm^2.

The correlation between GEM1 and SC counts per spill, integrated over the total number of pads and strips, respectively, is shown in Fig. 4; the GEM1 response is acceptably proportional within the explored range, with a calibration factor of 979 ± 16 counts per SC count. The FWHM of the beam was measured with GEM1 at the same time with a pad granularity of 2 mm and fitted in the horizontal direction with a Gaussian distribution. With the GEM1 it was found to be 9.2 ± 0.2 mm, agreeing with the SC measurement of 10.0 ± 0.1 mm.