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Monitoring of carbon ion therapeutic beams with thin silicon sensors

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ABSTRACT

Single ion counting in particle therapy may lead to new beam monitoring systems, enabling innovative delivery strategies that are faster and more sensitive than those currently used in clinics. Previous studies carried out by the University and the National Institute of Nuclear Physics (INFN) of Turin have demonstrated the feasibility of using thin silicon detectors to count single protons in clinical beams. The aim of this work is to report the performance of a strip-segmented 60-μm thick silicon PIN sensor used for single carbon ion discrimination. All measurements were performed using the CNAO synchrotron at different beam energies covering the clinical energy range (115–399 MeV/u). Signals from the sensor strips were read using a custom amplifier board and sampled with a 5 GS/s digitizer. The carbon ion signals were analyzed in terms of amplitude, duration, and deposited charge at different sensor bias voltages.

1. Introduction

Carbon ion radiation therapy (CIRT) takes advantage of the higher linear energy transfer (LET) and higher relative biological effectiveness (RBE) of carbon ions to target tumor cells while reducing radiation dose to adjacent normal tissues [1]. The National Center for Oncological Hadrontherapy (CNAO) in Italy performs clinical treatments with carbon ion beams delivered with a synchrotron [2]. In synchrotron-based facilities, beam extraction occurs in bunches, called spills. The measurement of relevant physical beam parameters is crucial to ensure uniform dose distributions during patient treatments [3]. However, there is currently a lack of detectors capable of providing online precise information on the microstructure of the spill [4].

For clinical beam delivery control, ionization chambers have been adopted worldwide as detectors for real-time beam monitoring, because they are very stable and robust in terms of radiation resistance [5]. However, they have some limitations such as low sensitivity ($\sim 10^4$ particles$\cdot$s^{-1}) and slow charge collection times ($\sim$100 μs) [6,7], which restrict their use for fast scanning and multiple rescanning needed to treat moving targets [8] and do not allow the control of the spill microstructure. In recent years, the University and the National Institute of Nuclear Physics (INFN) of Turin have demonstrated the feasibility of counting protons in therapeutic beams using thin Ultra-Fast Silicon Detectors (UFSD), segmented in strips [6,9]. These sensors have fast response times ($\sim$ ns), excellent time and spatial resolutions, and if properly segmented can be operated at high counting rates (up to 10^{10} particles$\cdot$cm$^{-2}\cdot$s^{-1}) in harsh radiation environments [6,10].

Exploiting the available sensors geometry developed for monitoring

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the proton therapeutic beams, a thin strip-segmented silicon PIN sensor, manufactured at the Fondazione Bruno Kessler (FBK), was characterized with the CNAO carbon ion beam in different experimental conditions. Taking advantage of the nanoscale temporal resolution of this detector readout by a digitizer, the signals for single carbon ions were studied for different beam energies and bias voltages, and the results are reported in this work.

2. Experimental setup description

A diagram showing the experimental setup used at CNAO is presented in Fig. 1. The device under test (DUT) was a 60 μm-thick planar silicon PIN sensor from the MoVe-IT 2020 production. It has a sensitive area of 7.8 × 5.5 mm^2 segmented in 11 strips (4 × 0.55 mm each) separated at 51 μm (see highlighted area on the left of Fig. 1). This sensor was previously characterized in the laboratory and all strips showed a breakdown voltage larger than 300 V [10].

The measurement setup included the silicon sensor with 8 strips bonded to an 8-channel custom front-end board, which amplifies the signal by a factor of about 100. As shown in Fig. 1, the 8 analogue outputs of the board were connected to a 16-channel digitizer to convert the amplified charge collected by the strip into a digital signal, exploiting the 12-bit resolution and an acquisition window of 204.8 ns allowed by the CAEN digitizer (model: *DT5742*, 5 GS/s). Simultaneously, the digitizer was connected via an 80 MB/s optical link to a PC, used to control the acquisition and to save the data for the offline analysis. A CAEN power supply (model: *DT1*47ET) was used to provide the bias voltage to the sensor. Both the power supply and the PC were controlled remotely via an Ethernet connection.

The sensor characterization with carbon ions was performed at CNAO using the monoenergetic clinical beams, which have energies in the range from 115.2 to 398.8 MeV/u. The beam shape is approximated to a Gaussian and the FWHM at the isocenter[2] varies from 0.60 to 0.95 mm (from the highest to the lowest energy). The ions are accelerated in bunches and delivered during the beam-on time, called spill. The spill duration depends on the number of particles needed and required for the defined depth; thus, it lasts approximately from tenths of ms to a few seconds [2,11]. The measurements were performed at four different beam energies and for nine sensor's bias voltages from 9 to 300 V. The nominal number of ions per spill was set to 5 × 10^7 and for each measurement condition data were taken for a minimum of 10 and up to 20 spills. The detector was first placed at the isocenter with its sensitive area perpendicular to the beam incidence direction, and then rotated by 40° around the vertical axis. It is worth mentioning that all the measurements were carried out at room temperature.

3. Results

Fig. 2a shows an example of typical waveforms, one per channel, after baseline subtraction, where each sharp peak corresponds to the signal produced by the large ionization charge of a single carbon ion in that specific strip. The distance from peaks of the same color shows the distance in time from consecutive ions, which can be intervals less than 10 ns, as shown for strip 3. The bipolar signals observed in the other strips in coincidence with the sharp signal are due to the crosstalk effect, i.e., signals induced in the adjacent strips by the incoming particle. The signal duration[3] as a function of the high voltage is shown in Fig. 2b where at lower voltages (less than about 50 V), the signals feature a long tail in the charge collection time while for values above 100 V the signals reach a minimum duration of about 2 ns.

The peak amplitude distribution for different beam energies as measured by a single strip is shown in Fig. 3a. In the wide clinical range, good separation between signals and noise was achieved and a unique threshold, independent from the energy, could be used to count the ions during the treatment. Good signal-noise separation is mandatory to achieve good counting efficiency and performance. The most probable values (MPV) of the amplitude, extracted from the fit of the data with the convolution of a Landau distribution with a Gaussian representing the noise, decreases for increased beam energy as expected from the Bethe-Bloch function.

By plotting the MPV of the peak amplitude as a function of the bias voltage for the detector placed at angles of 0° and 40°, a plateau is observed for values above 150 V (Fig. 3b). At these voltages, the electric field inside the detector is larger than 30 kV cm^{-1}, which is expected to saturate the drift velocity of the electrons in the detector at room temperature [10]. As expected, rotating the sensor 40° increases the signal amplitude (by a factor of ∼1.3), due to the longer travel path of carbon ions through the active thickness of the detector, thus creating additional charge carriers.

The measured deposited charge distribution, estimated as the

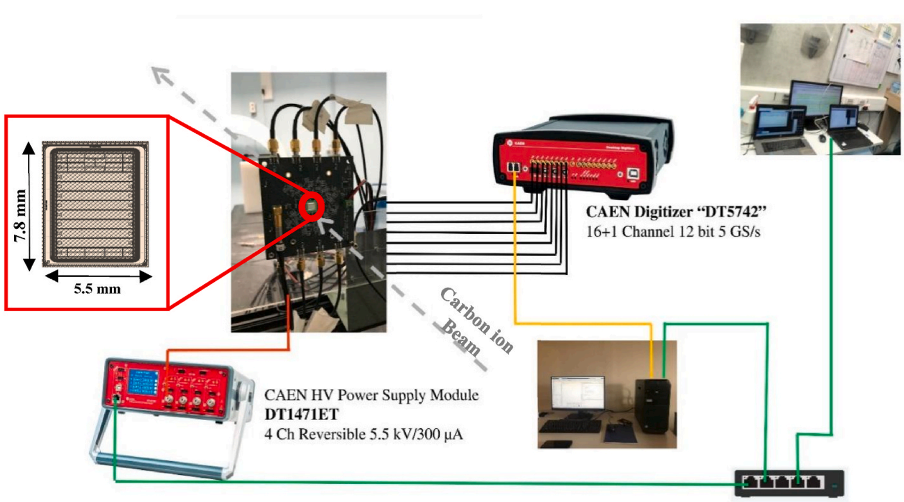

Fig. 1. Schematic representation of the experimental setup used at CNAO for the carbon ion measurements.

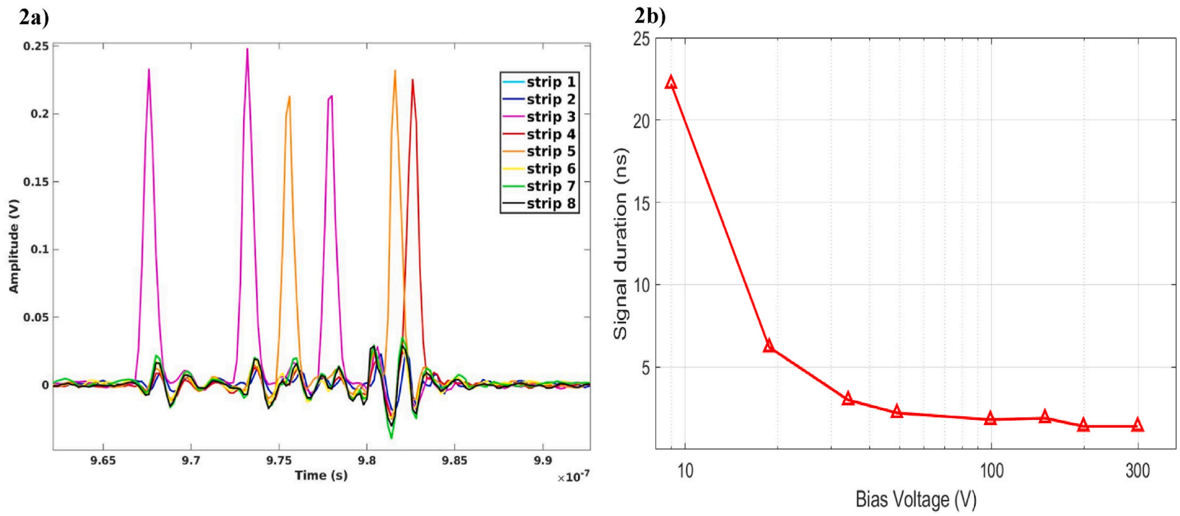

Fig. 2. a) A 30 ns time-interval zoom on a typical waveform showing the signals produced by 398.8 MeV/u carbon ions in different strips with a bias voltage of 149 V. b) Average signal duration for all strips as a function of bias voltage for carbon ions of 398.8 MeV/u.

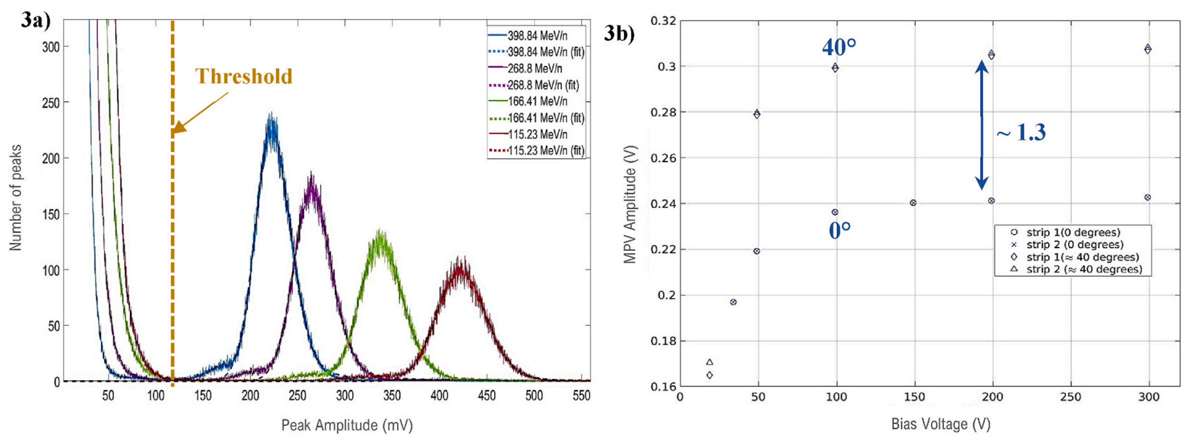

Fig. 3. a) Amplitude distribution of signals produced for carbon ions at four different energies in a single strip with a bias voltage of 149 V. b) MPV amplitude vs. bias voltage on two individual strips with the sensor placed at 0° and 40° angles for 398 MeV/u carbon ions.

integral of the peaks divided by the amplification and the input impedance of the digitizer (50 Ω), is found to vary with an MPV between 20 and 90 fC for all measured energies and bias voltages applied to the detector.

4. Summary

First tests of thin strip segmented silicon sensors with therapeutic carbon ions yielded promising results. The fast temporal response (∼ns) of the sensor allowed counting individual particles of a bundled carbon ion beam, obtaining well-defined sharp peaks. The peak amplitude distributions showed very good separation between signal and noise, scaling as expected with beam energy. It was observed that by rotating the sensor's active area with respect to the direction of beam incidence the MPV of the peak amplitude increased proportionally to the increased sensor thickness traversed by the ions, thus improving the signal-to-noise ratio. Furthermore, the signal duration decreases with increasing bias voltage, reaching values below 2 ns. The charge values deposited on the silicon strips ranged between 20 and 90 fC, for all energies covering the clinical range, and the bias voltages applied to the detector. These preliminary results indicate the feasibility of using thin sensors for therapeutic carbon ion beam monitoring.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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