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# Carbon ions tracking in particle therapy: first tests with thin silicon sensors

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**Introduction:**
The single particle tracking is a demanding task in clinical particle beams due to the high instantaneous fluence rate, up to $10^{10}$ protons/cm$^2$·s and $10^8$ carbon ions/cm$^2$·s. The aim of a fast and accurate (< 1% uncertainty) single particle counter is to overcome the slow charge collection times (hundreds of microseconds) and low sensitivity (thousands of particles) of the gas detectors currently employed in clinics, which limit the development of new faster and more accurate dose delivery strategies.
Over the last years, the INFN MoVeIT Project demonstrated the potential of using thin Low Gain Avalanche Diodes (LGADs) for counting protons and for developing time-of-flight applications to measure the particle' s beam energy. The design of sensors optimized for carbon ions are among the tasks of the new INFN-SIG project. To this goal, a subset of LGAD sensors segmented in strips and developed for protons were manufactured without implantation of the gain layer. The results of the first tests using a clinical carbon ion beam at CNAO (Pavia) will be reported.
**Materials and methods:**
The 8 central strips (4000 µm length and 591 µm pitch) of a PIN sensor of 60 µm active thickness were connected to a 8 channels custom frontend board providing a gain of about 2mV/fC. The output signals were sampled with a CAEN digitizer model DT5742, providing 5 GS/s with 12 bit resolution (1 ADC = 0.24 mV) in windows of 1024 samples.
The measurements were performed with 4 beam energies covering the clinical energy range (115, 166, 269 and 399 MeV/u), each run being characterized by consecutive spills with $8\times10^7$ ions delivered per spill at clinical beam intensities. Several runs were acquired at each beam energy varying the sensor bias voltages from 4 to 299 V and using two different beam incidence angles (0° and 40°). In each run, the peaks were selected in the waveforms and analyzed in terms of crossing time, amplitude and signal duration. Amplitude distributions were fitted using a convolution of a Landau with a Gaussian, the most probable value (MPV) being related to the average energy loss by the ions in silicon. Few runs with two detectors in coincidence were also preformed to measure the time resolution.
**Results:**
The peak amplitude distributions show a very good separation between signal and noise, with an MPV reaching the maximum at a sensor bias above 100 V and scaling with the beam energy, as expected by the Bethe-Bloch formula, and with the increase of the crossed thickness when the incidence angle is varied. Similarly, the signal duration decreases with the increase of the bias voltage up to 100 V, where it reaches a value of less than 2 ns. A single hit time resolution of about 25 ps is achieved at the two extreme energy values of 115 and 399 MeV/u. Studies of charge sharing and signal induction between adjacent strips indicate an overall negligible effect.
**Conclusions:**
Initial tests of thin silicon sensors segmented in strips irradiated with therapeutic carbon ion beams show very promising results, preparing the groundwork for future devices and applications for particle therapy based on the single ion tracking capability.

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