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Thin low-gain avalanche detectors for particle therapy applications

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Abstract. The University of Torino (UniTO) and the National Institute for Nuclear Physics (INFN-TO) are investigating the use of Ultra Fast Silicon Detectors (UFSD) for beam monitoring in radiobiological experiments with therapeutic proton beams. The single particle identification approach of solid state detectors aims at increasing the sensitivity and reducing the response time of the conventional monitoring devices, based on gas detectors. Two prototype systems are being developed to count the number of beam particles and to measure the beam energy with time-of-flight (ToF) techniques. The clinically driven precision ($< 1\%$) in the number of particles delivered and the uncertainty < 1 mm in the depth of penetration (range) in radiobiological experiments (up to 10^8 protons/s fluxes) are the goals to be pursued. The future translation into clinics would allow the implementation of faster and more accurate treatment modalities, nowadays prevented by the limits of state-of-the-art beam monitors. The experimental results performed with clinical proton beams at CNAO (Centro Nazionale di Adroterapia Oncologica, Pavia) and CPT (Centro di Protonterapia, Trento) showed a counting inefficiency <2% up to 100 MHz/cm^2, and a deviation of few hundreds of keV of measured beam energies with respect to nominal ones. The progresses of the project are reported.

1. Introduction

The sensitivity of ionization chambers (ICs), the state-of-the-art beam monitors in charged particle therapy, limits the minimum number of particles that can be safely delivered to the order of thousands per spot, while their slow collection time (hundreds of microseconds) precludes the use of ICs on fast beam delivery strategies (1). Any innovative treatment modalities, such as the ones using less radiation and being faster, cannot be implemented without developing a monitoring system meeting the clinically driven precision of less than 1% in the number of particles delivered and the uncertainty of less than 1mm in the depth of penetration. Within the MoVeIT (Modeling and Verification for Ion beam Treatment planning systems) project, the University of Torino (UniTO) and the Torino section of the

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National Institute for Nuclear Physics (INFN-TO) are exploring the direct measurement of beam particles as new monitoring approach in particle therapy (2). Two prototypes, the first one aimed at counting the number of beam particles up to a fluence of 100MHz/cm^2 and the second one to measure the beam energy with time-of-flight (ToF) techniques, are being developed exploiting the innovative Ultra Fast Silicon Detector (UFSD) technology. Dedicated UFSD strips sensors have been designed and produced at the Fondazione Bruno Kessler (FBK, Trento), along with a fully custom front-end readout. This work reports the progresses of the project.

2. Materials and Methods

2.1. Ultra Fast Silicon Detectors (UFSD)

UFSD are n-on-p silicon sensors, based on the Low Gain Avalanche Detectors (LGAD) design, allowing concurrently accurate measurements of time and space in segmented sensors (3).

Three UFSD sensor geometries have been designed and developed for the MoVeIT project. In order to juxtapose sensors and cover a 3x3 cm^2 field of view, two sensor geometries have been designed for counting purposes, with either 30 strips (150 µm pitch) or 20 strips (200 µm pitch), both with an active thickness of 50 µm, a total thickness of 600 µm, and a single strip area of 2 mm^2 and 5 pF of capacitance. The timing sensor holds 11 strips (590 µm pitch) of 2.2 mm^2 area each, with a 50 µm active thickness, and a total thickness of 70 (or 100 µm) obtained after a mechanical thinning procedure. Different doping options of the sensors gain layer (Gallium or Boron), different thermal cycles and treatments with carbon spray were studied to compare the resistance to the radiation damage. An energy measurement test was performed at CNAO using Hamamatsu Photonics K.K. (HPK) sensors, segmented in 4 pads, each one characterized by a sensitive area of 3x3 mm^2 and depleted region of 80 µm thickness.

2.2. ASIC chip

The MoVeIT single ion discriminator prototype aims at counting the number of protons within 1-2% accuracy for particle fluence rates up to 10^8 cm^{-2} s^{-1}, which results in a maximum instantaneous rate of 2 MHz per channel considering the sensor strip segmentation. Assuming a Poissonian distribution of the particles inside the beam structure and considering a paralyzable model for describing the saturation effects due to signal overlapping, a front-end dead time $\leq$ 10 ns (i.e. a discrimination frequency up to 100 MHz) is necessary to achieve the required accuracy in discriminating signals. The charge produced in a typical 50 µm thick LGAD sensor with a gain of 10 can vary from 4 fC to 150 fC, taking into account the therapeutic energies (60 – 250 MeV) and the expected Landau fluctuations in the charge production. A dedicated 24 channels custom front-end ASIC prototype, nicknamed ABACUS (Asynchronous-logic-Based Analog Counter for Ultra fast Silicon strips), has been designed in a CMOS 110 nm technology, based on a fast amplifier with self-reset capabilities (4).

2.3. Beam tests

The sensors were fully characterized in our laboratory, and tested on the clinical proton beams of the CNAO (synchrotron, 10 mm FWHM proton beam with a flux range 10^8 – 10^9 protons/s, in spills) and CPT (cyclotron, 3-7 mm FWHM proton beam with a flux range 10^6 – 10^{10} protons/s), considering all the energies in the therapeutic range (60 – 230 MeV). For both tests, the sensors were glued on high voltage distribution boards aligned to the beam, two out of the total number of sensor channels (either 30 or 20 for counting sensors, 11 or 4 for timing goals) were fed into low-noise current amplifiers (C2 CIVIDEC Instrumentation, Austria; 2 GHz analogue bandwidth; 40 dB gain), and readout by a 16+1 channel digitizer desktop module (DT5742 CAEN, Italy; 5 GSample/s). A PC connected to the digitizer with an 80 MB/s optical link was used to control the acquisition and collect the waveforms.

For the ion discriminator prototype, the charged measured by a PTW pin-hole ionization chamber, put along the beam direction right after the sensor, was used for an independent estimation of the particle rate. The particle rate was measured by the counting detector, varying the flux within the available range at the two facilities, for different energies.

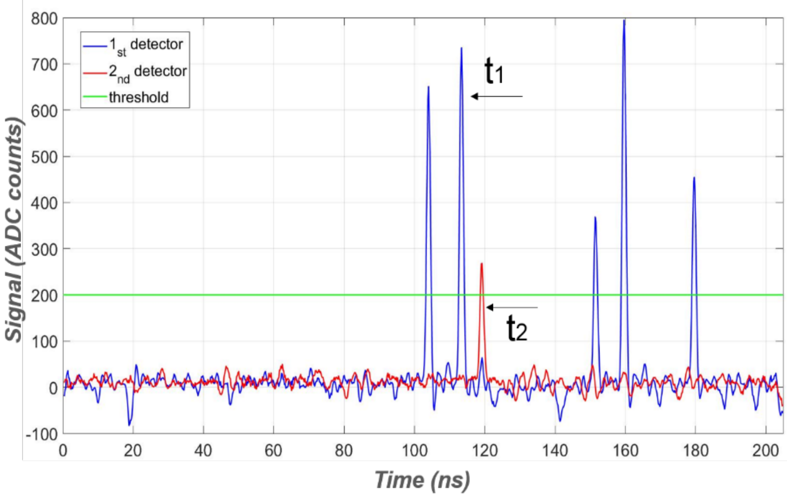

Figure 1. Example of a 200 ns waveform acquired by the digitizer, showing the signals of the first (in blue) and second (in red) detectors at a relative distance of 970 mm in the telescope system, for a beam energy of 182.8 MeV at the CPT facility. The arrows point out the time of arrival of two possible coincident signals in the first (t_1) and second (t_2) detectors. The green line corresponds to the threshold used to identify the signals from background noise.

For the assessment of the beam energy, a telescope of two UFSD sensors was built for accurate ToF measurements. For each distance L between the sensors (S_1 and S_2), the times t_1 and t_2 compatible with the same particle crossing S_1 and S_2 were identified from the waveforms collected by the digitizer (Fig. 1), using a constant fraction algorithm to minimize time-walk effects. From the difference Δt (i.e. $t_2 - t_1$) and the known distance L between S_1 and S_2, the beam mean velocity v and the kinetic energy K were determined, taking into account several systematic effects, such as the beam energy loss in the first silicon sensor and in air, and performing a system calibration. Assuming the nominal energies as known, a chi-squared minimization method was adopted to calibrate the system in terms of the distance between the sensors and the time-offset, basically due to the routing of the electronic chain, using the ToF measurements performed at all the energies tested for each of the distances considered.

3. Results

The achieved efficiency of the counter prototype was > 98% up to a local beam flux of 10^8 protons/s·cm^2, i.e. a rate of 2 MHz per 2 mm^2 channel, as shown in Fig. 2.

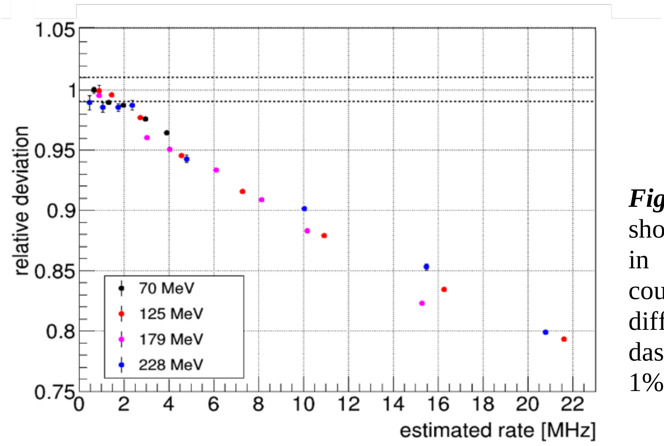

Figure 2. Different colors show the relative deviation in the particle rate (i.e. counter efficiency) at different beam energies. The dashed lines highlight the 1% relative deviation.

The root mean square deviation of the energy residuals (measured – nominal beam energy) at 97 cm distance between S_1 and S_2 for all considered beam energies in the range 60 – 230 MeV was 280 keV at CNAO and 341 keV at CPT, corresponding to a range uncertainty < 1 mm, as clinically required.

The silicon pads used at CNAO (80 µm active area thickness) showed a time resolution for single particle crossing of 75 – 115 ps, while the silicon strips used at CPT (50 µm active area thickness) showed a time resolution of 40 – 75 ps.

Although the data acquisition and throughput were not optimized, a beam irradiation of less than 6 s (at therapeutic fluxes, 228 MeV proton beam energy, and at 1 m distance between sensors) was enough to collect the statistics required to keep the error on the ToF below the values needed to obtain the clinically required range uncertainty (< 1 mm).

4. Discussion

The first experimental results confirmed the counting and timing capabilities of UFSDs, encouraging their potential role into the improvement of therapeutic beams monitoring. However, the roadmap towards their application into clinics just started. Indeed, the 98% efficiency of the counter prototype achieved for local beam fluxes up of 10^8 protons/s·cm^2 needs to be further improved to cope with therapeutic fluxes, and reliable correction algorithms for pile-up effects should be studied and implemented. Both counting and timing sensors are being integrated with the dedicated readout electronics in order to readout all the strips and obtain the final prototypes, which will be tested in clinical facilities. The readout of all available strips, together with a dedicated algorithm to properly analyze the coincident signals among the multiple sensor channels, will increase the statistics of the acquired coincident events in the telescope system for the energy measurement prototype. Along with the proper optimization of data acquisition and throughput, this will reduce the irradiation time needed to assess the beam range with ToF techniques, setting-up an “online” energy measurement system. The sensors have been carefully designed and produced to optimize their radiation hardness and dedicated studies will focus on early performance degradation.

5. Conclusion

Innovative silicon detectors (UFSD) are being designed and developed to build a single ion discriminator and a beam energy measurement device for beam monitoring in proton therapy. The preliminary experimental results performed at CNAO (Pavia) and CPT (Trento) allowed achieving an efficiency of the counter prototype > 98% up to a local beam flux of 10^8 protons/s·cm^2 and a difference between the measured and the nominal energies of few hundreds of keV, exploiting a telescope system for ToF measurements.

6. References

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