Monitoring therapeutic proton beams with LGAD silicon detectors

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ABSTRACT: The University and the National Institute for Nuclear Physics of Torino are developing LGAD-based prototypes for beam monitoring in proton therapy. The direct measurement of single beam particles could overcome some features of currently used ionization chambers, such as slow charge collection and reduced sensitivity, which limit the implementation of advanced delivery techniques (e.g. rescanning). LGAD strip sensors have been designed and produced by Bruno Kessler Foundation (FBK, Trento) specifically for this project. A counter prototype to directly count individual protons at clinical fluence rates (10^6-10^{10} protons/cm^2·s) and a telescope system to measure the beam energy with time-of-flight (TOF) techniques are described. Tests of LGAD silicon strip sensors performed on synchrotron and cyclotron beams of therapeutic centers, using a pin-hole ionization chamber for the independent measurement of the particle flux, already showed the possibility to keep the counting error < 1 % up to a beam fluence rate of few 10^8 protons/cm^2·s. The ongoing tests of counting sensors readout by a dedicated fast Charge Sensitive Amplifier chip are reported. The telescope system, made of two sensors at a distance up to 95 cm, allows measuring the beam energy in the clinical range (70-230 MeV) with a maximum deviation of 310 keV in respect to the nominal one, with an uncertainty of 500 keV, thus achieving the prescribed clinical accuracy of 1 mm in the range in water.

KEYWORDS: particle therapy, beam monitors, silicon detector

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Contents

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1. Intro

Within the MoVeIT project, the University and the National Institute for Nuclear Physics of Torino are proposing the direct measurement of particles using LGAD-based innovative detectors for monitoring clinical proton beams [1,2]. This approach has the potential to overcome the limits of current beam monitors, such as slow charge collection times, thus supporting the future implementation of advanced and fast delivery techniques (e.g. fast rescanning modalities) in particle therapy. This contribution reports about the status of the project.

2. Materials and Methods

2.1 Thin LGAD silicon sensors

Ultra Fast Silicon Detectors (UFSD) are based on Low Gain Avalanche Detectors (LGAD) design, characterized by small thicknesses (typically ~50 µm) and controlled low gain (~10-30), providing an enhanced signal in thin detectors with the same noise level of traditional silicon sensors of similar geometry, with very short time duration (ns), allowing particle counting, and excellent time resolution (ps), allowing beam energy measurement through TOF techniques [3]. Thin planar UFSD prototypes were specifically designed and produced for the MoVeIT project by Bruno Kessler Foundation (FBK, Trento, Italy). Strip segmentation has been chosen for all structures (reported in Table 1) in order to reduce the expected particle rate per channel and the

Table 1. Characteristics of the MoVeIT sensors for counting and timing purposes.

	Number of strips	Strip length	Strip area	Active thickness
Counting sensor (short)	20	1.5 cm	2.2 mm^2	60 µm
Counting sensor (long)	30	3.0 cm	2.4 mm^2	60 µm
Counting sensor (final)	144	2.6 cm	3.0 mm^2	50 µm
Timing sensor	11	4.0 mm	2.2 mm^2	55 µm

sensor capacitance. The final counting sensor, whose sensitive area (~2.7x2.7 cm^2) was defined to cover the clinical proton beam cross section characterized by a FHWM of ~1 cm at the isocentre, is described in more details in the contribution of [4].

2.2 Counting

A dedicated fast Charge Sensitive Amplifier chip (ABACUS [5], Fig. 1a and 1b) with an area of 2x5 mm^2 and 24 channels has been designed to discriminate the expected signal pulses in a wide charge range (3-150 fC, corresponding to the energy released in silicon by clinical protons of 60-230 MeV) with a maximum dead-time of 10 ns to minimize pile-up counting inefficiencies at clinical fluence rates (10^6-10^{10} protons/cm^2·s).

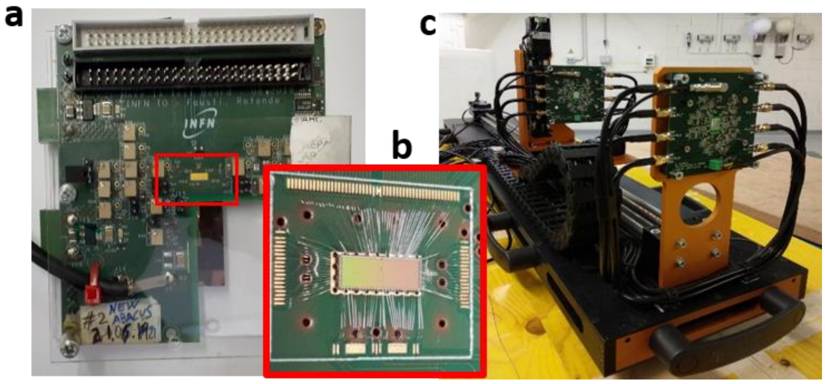

Figure 1. a. Test-board mounting a counting long strip readout by an Abacus chip, zoomed in **b**. **c.** Telescope system prototype for TOF measurements.

The outputs of the chip are sent to an FPGA for the pulse counting, and the FPGA is connected to a computer where a dedicated LabVIEW program controls and integrates the FPGA input-outputs, displays online the counting rate from each strip and stores the useful data. The same FPGA is also used to initialize the chip by setting the local DACs of the chip channels.

2.3 Timing

Timing sensors (Table 1), thinned down to a total thickness of 70 µm to minimize the beam perturbation, are readout by dedicated boards with two stages of amplification optimized for time measurements with large signals (3-150 fC charge dynamic range) at high fluxes (10^9 p/cm^2·s). Signals generated by incoming protons are first amplified by the front-end electronics and then readout by a 16+1 channels digitizer (5 GS/s, 12 bits resolution) controlled by a PC with an 80 MB/s optical link. A prototype of telescope made of two timing sensors aligned along the beam direction has been built (Fig. 1c). The first sensor is kept fixed at the isocenter of the beam distribution system, whereas the second sensor can be moved in the transversal plane (x-y) for the alignment of the telescope with the beam trajectory, and along the longitudinal direction (z axis) to vary the distance between the two sensors from 300 mm to 950 mm. An optical encoder (0.01 µm resolution) provides the measurement of the position displacements of the second sensor. Starting from the measured time differences of coincident protons crossing the two detectors for different beam energies and distances between the sensors, the mean kinetic energy of the beam can be determined and finally the range in water, which is the clinically relevant parameter [6]. A self-calibration method, where only the measured mean time differences and the relative displacements are used as input parameters, has been implemented to remove the systematic errors due to the experimental setup, independently from any a priori knowledge of the beam parameters (the method is object of the Italian Patent Application No. 102021000025190).

3. Results

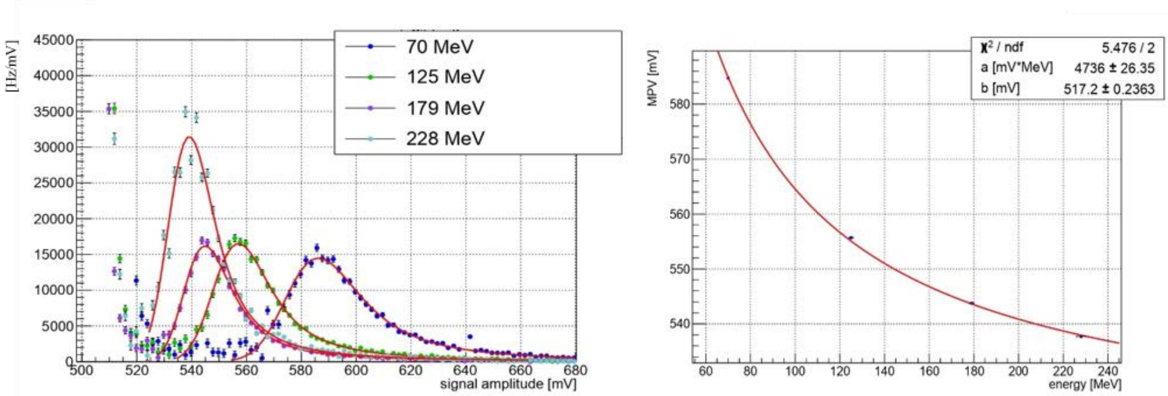

Figure 2. *Left.* Signal amplitude distribution obtained from 1 chip channel fitted with convolution of Landau and Gaussian (red curves) for 4 beam energies. *Right.* Most Probable Values (MPV) vs energies.

Tests of LGAD silicon sensors performed on synchrotron and cyclotron beams of therapeutic centers, using a pin-hole ionization chamber for the independent measurement of the particle flux, showed the possibility to keep the counting error < 1% up to a beam fluence rates of few 10^8 p/cm^2·s [2]. Algorithms based on logical combinations of signals from two independent detector channels under the same radiation field are being developed for count-loss correction at fluence rates up to 10^{10} p/cm^2·s [7]. To characterize the counting prototype (sensor + asic), threshold scans (rate as a function of the threshold voltage set in the leading-edge discriminator of each channel) have been acquired with different proton beam energies (70-228 MeV) at the Trento Proton Therapy Center. The signal amplitude distribution of one channel, obtained through the discrete derivative of the threshold scan, is shown in Fig. 2. The Most Probable Values, obtained by fitting the amplitude distributions with the convolution of a Landau and a Gaussian, vs the beam energy

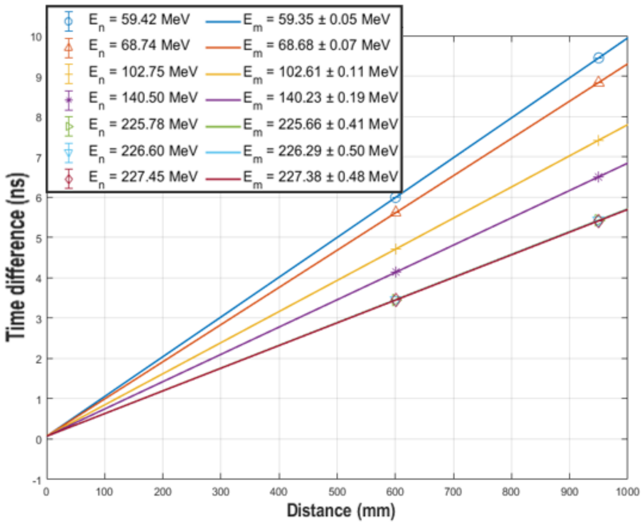

Figure 3. Time difference vs distance for two distances (600 and 950 mm) between the sensors of the telescope and 7 beam energies. The legend shows the nominal energy (E_N, retrieved from the Bragg peak positions measured by CNAO using a Peakfinder water column with a maximum deviation within ±0.15 mm) and the measured energy (E_M).

reproduce the mean energy loss per unit path length described by the Bethe Bloch formula, as expected (Fig. 2).

For TOF measurements, the self-calibration method allowed defining the time offsets between different combinations of strips in sensor 1 and sensor 2. These time-offsets were used to correct the time-of-arrival differences of protons crossing sensor 1 and sensor 2 of the telescope, for different beam energies and 2 distances between the sensors (Fig. 3) at CNAO (Pavia). A maximum deviation of 310 keV between nominal and measured energies, obtained from the linear interpolation of time differences vs distance, have been observed with a uncertainty of 0.5 MeV on the measured energy, thus achieving the prescribed clinical accuracy of 1 mm in the range in water (Fig. 3).

4. Conclusion

This contribution reports about the status of the development of two prototypes, based on the UFSD technology, for online monitoring of clinical proton beams: the first one to directly count individual protons and the second to measure the beam energy with time-of-flight (TOF) techniques. The final counting prototype, featuring a 2.7x2.7 cm^2 sensor with 144 strips and its custom readout will be tested in the next months, while the promising results of the telescope system suggests its future use in beam quality control procedures.

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