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Test of innovative silicon detectors for the monitoring of a therapeutic proton beam*

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Abstract. Beam monitoring in particle therapy is a critical task that, because of the high flux and the time structure of the beam, can be challenging for the instrumentation. Recent developments in thin silicon detectors with moderate internal gain, optimized for timing applications (Ultra Fast Silicon Detectors, UFSD), offer a favourable technological option to conventional ionization chambers. Thanks to their fast collection time and good signal-to-noise ratio, properly segmented sensors allow discriminating and counting single protons up to the high fluxes of a therapeutic beam, while the excellent time resolution can be exploited for measuring the proton beam energy using time-of-flight techniques. We report here the results of the first tests performed with UFSD detector pads on a therapeutic beam. It is found that the signal of protons can be easily discriminated from the noise, and that the very good time resolution is confirmed. However, a careful design is necessary to limit large pile-up inefficiencies and early performance degradation due to radiation damage.

1. Introduction

Monitoring the dose in particle therapy is equivalent to ensuring that the prescribed number of particles of a given energy is delivered at each specific location in the target. Given the high fluxes of a therapeutic beam, fast and accurate beam monitoring can be a challenge, particularly for those active beam scanning systems where a pencil beam is scanned at high speed across the irradiation field.

Beam monitoring is typically carried out by using parallel plate ionization chambers working in transmission mode [1]. Although being robust and reliable, gas detectors are affected by a limited sensitivity, slow response time and charge recombination effects, and they need to be calibrated daily against standard dosimeters and their dependence on beam quality factors such as beam energy, fluence, fluence rate etc. and need to be fully characterized and controlled with high accuracy [2].

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Solid state detectors, being much faster and with better sensitivity, would allow to overcome these limitations.

Recent developments in silicon detectors with moderate internal gain (Low Gain Avalanche Detectors, LGAD [3]) offer a promising technological option. These detectors, named Ultra Fast Silicon Detectors (UFSD) [4], are thin n-in-p LGADs optimized for timing applications where a moderate internal gain (~ 5-20) is achieved by charge multiplication in the strong electric field induced by an addition p+ doping layer implanted under the n++ cathode, at a few µm depth. This allows producing thin detectors with very fast signal collection time (~ 1 ns in 50 µm thickness), excellent time resolution and with a signal-to-noise ratio, increasing with the bias voltage, similar or better than traditional silicon sensors. Thanks to these properties, properly segmented UFSD sensors could allow discriminating and counting single protons up to the high fluxes of a therapeutic beam while the excellent time resolution suggests using time-of-flight techniques for measuring the proton beam energy.

The MoVeIt project, promoted by the Italian National Institute for Nuclear Physics (INFN), aims at developing two devices based on UFSDs, one for particle counting and one for the measurement of the beam energy, to characterize a therapeutic beam in radiobiological applications. We report here the results of the first tests performed with UFSD detector pads on a therapeutic beam.

2. Materials and Methods

Beam tests were performed at the CNAO particle therapy facility (Pavia, Italy) on the therapeutic proton beam. The data were acquired in 32 runs, $2*10^{10}$ protons per run, with a nominal beam FWHM of 1 cm and at a fixed beam energy selected in the range 62 to 227 MeV. Different beam fluxes were also used, ranging from 20% up to 100% of the maximum flux (about $5*10^{9}$ p/s). Two UFSD sensor pads of 50 µm active thickness (rectangular 1,2 x 1,2 mm^2, produced by CNM-Barcelona, and circular 1 mm Ø, manufactured by the Hammamatsu company) were positioned aligned among themselves and to the beam at a mutual distance of 1 cm, enclosed in a metallic box with a beam entrance hole. The signals of two sensors were fed into CIVIDEC broadband amplifiers [5], 40 dB gain, and acquired with a CAEN DT5742 digitizer [6], providing waveforms of 200 ns duration at 5 GS/s sampling rate. The setup also included a PTW T31015 PinPoint [7] ionization chamber, positioned behind the two sensors and aligned to the beam, used to provide a relative measurement of the rate through the charge read out by an electrometer at fixed time intervals. The acquired waveforms were later used to analyze the counting and timing properties of the detectors.

3. Results

A typical waveform recorded by the digitizer is shown in figure 1A. Several features can be observed.

The pulse signal left by the crossing of a proton can be easily discriminated from the noise background; it has very short duration, approximately 2 ns and a varying amplitude reflecting the Landau charge fluctuations. A partial overlapping of two signals is also present, indicating that pile-up effects are present and can lead to counting inefficiency. A threshold was applied to count the pulses in each waveform and special algorithms were used to resolve, whenever possible, partially overlapping peaks.

By applying a threshold scan, the amplitude distribution was obtained as shown in figure 1B. A good separation between the signal amplitude distribution, well described by the Landau formula, and the background is observed. The Landau most probable value is larger at lower beam energies, where a larger energy loss occurs in the silicon, indicating that the optimal threshold should be beam energy dependent. We observe that the signal amplitude depends on the internal gain of the sensor which can be increased by applying a larger bias voltage; it was proven that, by a proper choice of this voltage, a good separation of the signal from the noise can be achieved even at the largest beam energy, where the smallest ionization is induced in the sensors.

The pile-up inefficiency is a serious concern for the counting application. It was estimated by comparing the reference rate, provided by the PinPoint chamber described earlier, with the measured pulse rate on the detector. Several runs were acquired at different beam energies and fluxes and the corresponding pulse rates were measured.

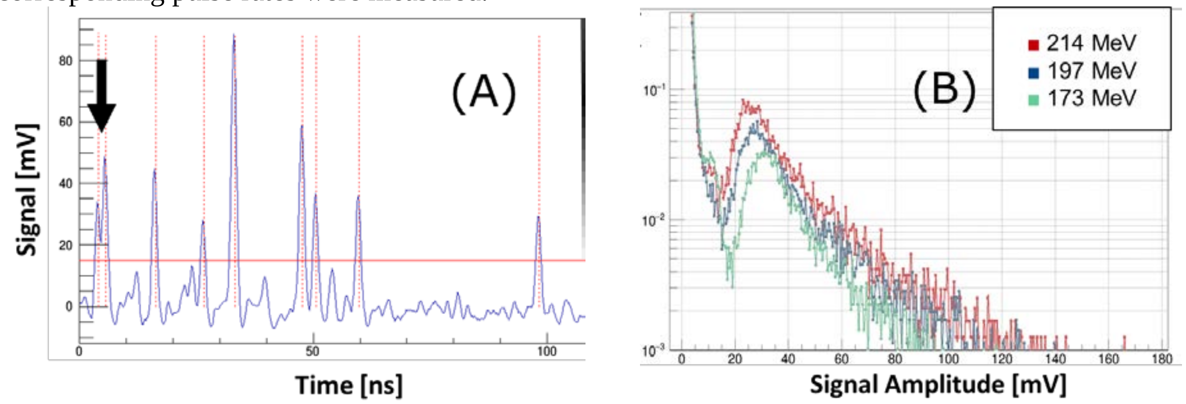

Figure 1. (A) Example of a portion of a time window collected with the digitizer. The arrow points at a peak where signal pile-up occurs, while the solid red line indicates the threshold applied for counting the pulses (9 pulses are found in this example). (B) Amplitude distribution of the pulses for three different beam energies with the CNM detector biased at 250 V. The vertical scale is in arbitrary units.

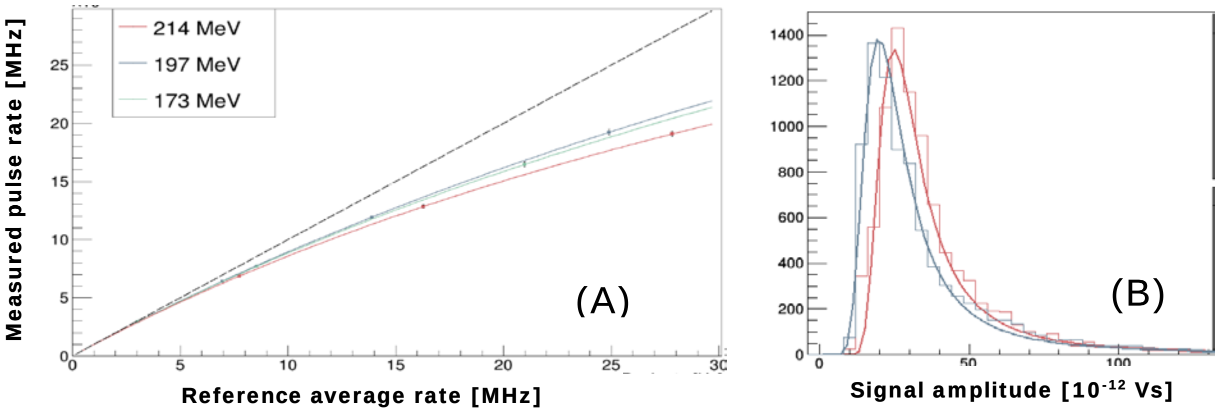

Figure 2. (A) Measured pulse rate (dots) as a function of the average particle rate on the detector for three different beam energies; curves are the results of a fit with a model describing pile-up effects. (B) Amplitude distribution before (red) and after (blue) fluence of 10^{12} p/cm^2; the curves are the results of a fit to the Landau distribution.

The results are shown in figure 2A where a deviation from linearity is observed at an average rate of protons above 5 MHz. The data were fitted to a pile-up model assuming a poissonian arrival time distribution and a fixed acquisition dead time [8]. The model was found to describe the results with an acquisition dead time of about 10 ns, i.e. much larger than the 2 ns pulse duration observed in figure 1A. The reason of this discrepancy originates from the non-poissonian time structure of the CNAO beam, where protons are delivered in bunches with a frequency of few MHz, leading to a pile-up probability larger than for a beam with a uniform time distribution of particles.

A second concern is the degradation of the performance after the irradiation of the sensor leading to loss of gain, already observed and documented [9]. It is believed that the boron dopant of the gain layer gets deactivated by irradiation, becoming interstitial in the silicon crystal. Figure 2B shows the pulse amplitude distribution of the CNM sensor measured with the same beam conditions before and after a fluence of approximately 10^{12} p/cm^2; indeed, a gain loss of about 20% is observed.

Finally, the time resolution was also measured by measuring the difference in time between pulses on the two sensors. The resolution on this quantity was found to be approximately 50 ps, resulting in 35 ps time resolution for each sensor. This confirms the excellent timing properties already reported in previous studies [10].

4. Outlook and Conclusions

Based on the results described above, detectors segmented in strips were chosen for the particle counter since they provide the granularity needed to limit the pile-up effect without the readout complexity of pixelated sensors. Samples with two strip geometries (15 and 30 mm length, with a pitch of 216 and 146 μm respectively) were designed and included in a multi-project production by FBK (Trento, Italy). Similar structures without gain layer were added for comparison. Different wafers were produced with different doping doses and modalities for the gain layer with the aim of improving the radiation resistance. In some wafers the boron implant was replaced by gallium and/or a high level of carbon was added to reduce the deactivation of the dopant.

A full characterisation is ongoing which includes laboratory measurements, beam tests and irradiation studies. As an example, figure 3 shows the comparison of the signal measured by two adjacent strips of two sensors, one with and one without gain layer, obtained by scanning orthogonally to the strips with an infrared laser beam. A gain of about 4 is observed, with a dead area between the strips of about 60 μm, in agreement with the results of the simulations of the sensor.

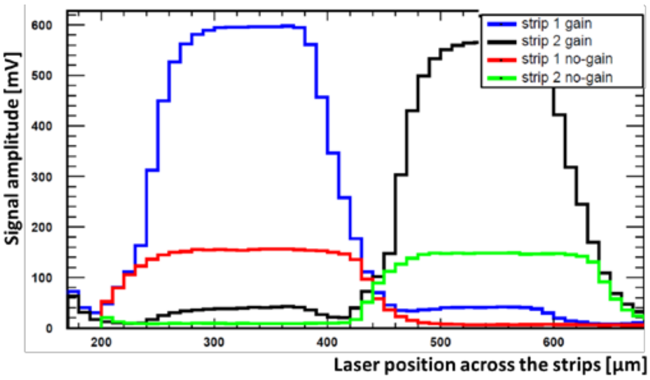

Figure 3. Signal amplitude as a function of the position across two strips. A laser source of 1060 nm wavelength and 20 μm spot size was used for this measurement. Both strips with and without gain are shown for comparison.

In parallel, the design of the readout chip for the counter, featuring a preamplifier followed by a comparator with a programmable threshold, is in an advanced stage. The prototypes of detectors and readout chips will be integrated in a front-end board connected to a commercial FPGA where the counting and the pile-up correction algorithms will be implemented and tested.

To conclude, the tests performed so far indicate that UFSDs are a viable option for improving the qualification and the monitoring of a therapeutic proton beams. A careful design effort is ongoing to limit pile-up inefficiencies and the observed early performance degradation.

5. References

[1] Giordanengo S *et al* 2013 *Nucl. Instr. Meth. Phys. Res.* A **698** 202-7
[2] Vial P *et al* 2008 *Med. Phys*. 35 1267-77
[3] Fernandez P *et al* 2011 *Nucl. Instr. Meth. Phys. Res.* A **658** 98-102
[4] Sadrozinski H W *et al* 2013 *Nucl. Instr. Meth. Phys. Res.* A **730** 226-31
[5] https://cividec.at/index.php?module=public.product&idProduct=33&scr=0
[6] http://www.caen.it/csite/CaenProd.jsp?parent=14&idmod=651
[7] http://www.ptw.de/pinpoint_chambers1.html
[8] Pommé S, Fitzgerald R and Keightley J 2015 *Metrologia* **52** S3-17
[9] Kramberger G *et al* 2015 *JINST* **10** P07006
[10] Cartiglia N *et al* 2017 *Nucl. Instr. Meth. Phys. Res.* A **850** 83-8