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ABSTRACT: To fully exploit the physics potentials of particle therapy in delivering dose with high accuracy and selectivity, charged particle therapy needs further improvement. To this scope, a multidisciplinary project (MoVeIT) of the Italian National Institute for Nuclear Physics (INFN) aims at translating research in charged particle therapy into clinical outcome. New models in the treatment planning system are being developed and validated, using dedicated devices for beam characterization and monitoring in radiobiological and clinical irradiations. Innovative silicon detectors with internal gain layer (LGAD) represent a promising option, overcoming the limits of currently used ionization chambers.

Two devices are being developed: one to directly count individual protons at high rates, exploiting the large signal-to-noise ratio and fast collection time in small thicknesses (1 ns in 50 μm) of LGADs, the second to measure the beam energy with time-of-flight techniques, using LGADs optimized for excellent time resolutions (Ultra Fast Silicon Detectors, UFSDs).

The preliminary results of first beam tests with therapeutic beam will be presented and discussed.

KEYWORDS: Charged particle therapy; Fast silicon sensors; Particle counter.

1. Introduction

Ionization chambers are currently used in charged particle therapy to monitor the beam, by measuring the beam flux and the beam position through the collection of the free charges generated by ionization effects in a gas volume, confined between a pair of metal electrodes. Although robust and easy to operate, these detectors suffer from slow response time, reduced sensitivity at low fluxes, response dependence on beam energy, and require daily calibrations.

Recently, the medical physics group of the Turin division of the National Institute of Nuclear Physics (INFN) is working in developing a new generation of silicon detectors able to count single particles of therapeutic beams, and to measure the beam energy with time-of-flight techniques. This represents a task of the interdisciplinary project MoVeIT (Modeling and Verification for Ion beam Treatment planning), involving the collaboration of various INFN groups.

MoVeIT aims at developing innovative treatment planning systems, integrating new biological models to consider the biological impact of different effects, such as target fragmentation, Relative Biological Effectiveness and intra-tumor heterogeneity, such as hypoxia. To validate those new models, dedicated devices for beam characterization and monitoring in radiobiological and clinical irradiations are requested.

Innovative silicon Low Gain Avalanche Detectors (LGAD), optimized for excellent time resolutions and therefore named Ultra Fast Silicon Detectors (UFSDs) [1], represent a promising option for this scope. In fact, the use of this type of detectors in charged particle therapy could lead to the detection of single ions and to count the number of beam particles with high precision, therefore improving the indirect measure provided nowadays by ionization chambers.

UFSDs are n-on-p silicon sensors featuring an internal moderate gain due to a thin p+ and low resistivity diffusion layer. The layer is located close to the bottom side of the n++ electrode of a heavily doped junction. Basically, the particle crossing the sensor releases charge carriers ionizing the medium. When the charges cross the gain layer, charge multiplication occurs followed by its collection at the electrodes [2]. The gain is limited to a value 10-20 in order to reduce noise perturbations and electric field confinement complexity in segmented detector configurations [2].

The main advantage of a UFSDs is to provide an enhanced signal in thin detectors with similar noise level of a traditional silicon sensor of the same geometry. This allows producing detectors as thin as 50 µm, providing signals of very short time duration and excellent time resolution. Moreover, the signal-to-noise (S/N) ratio of UFSDs can be increased by increasing the voltage bias, and this allows to better separate the noise from the signal [3].

Two UFSD devices are being developed within the MoVeIT project. The first one is aimed at directly counting individual protons at high rates, exploiting the large S/N ratio and fast collection time in small thicknesses (1 ns in 50 µm) of LGADs. Such a device, requiring UFSDs segmented in strips and front-end electronics, will also measure the beam profiles in two orthogonal directions. The goal of the second device is the beam energy measurement with time-of-flight techniques, exploiting the outstanding time resolution of UFSDs. A telescope of two UFSDs sensors segmented in a minimum number of pads (depending on the acceptable capacitance) will be used, and custom VLSI electronics with the proper channel density will be developed.

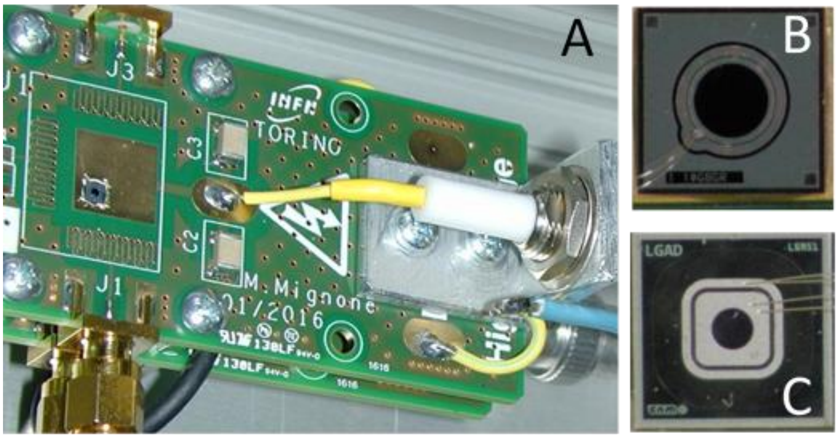

Figure 1. A. Picture of the two sensors mounted in a metallic box and aligned to the beam. B. Hamamatsu sensor (1 mm Ø x 50 µm thickness). C. CNM sensor (1,2 x 1,2 x 50 µm thickness).

The aim of the present work is to describe the preliminary tests of UFSDs sensors with a therapeutic beam.

2. Materials and Methods

Three beam tests have been performed at the CNAO particle therapy center (Pavia, Italy) with the therapeutic proton beam, to evaluate the counting and timing properties of UFSDs. The results here presented have been obtained via offline analysis of the collected waveforms acquired during 32 runs ($2*10^{10}$ p each run, beam FWHM = 1 cm), with fixed proton beam energy in each run ranging from 62 to 227 MeV, and different fluxes (ranging from 20% up to 100% of the maximum flux). Two sensors pads of 50 µm active thickness (1,2 x 1,2 mm^2, 1 mm Ø) have been mounted at a distance of 1 cm from each other in a metallic box, to keep them aligned among themselves and to the beam. The two outputs were fed into broadband amplifiers

(CIVIDEC 40 dB [4]), visualized through an oscilloscope (Teledyne Lecroy WaveRunner 640Zi, 40 GS/s sampling rate [5]), and acquired through a digitizer (CAEN DT5742, 5 GS/s sampling rate [6]), providing snapshots of 200 ns duration. The setup also included a PTW PinPoint ionization chamber (T31015 [7]) aligned to the beam after the sensors, used to provide a reference rate, HV and LV power supplies, and two computers, one in the treatment room and one in the control room to acquire the measurements and to remotely control all the instrumentations. Figure 1 shows the sensors used in the test.

3. Results

The recorded time windows of the digitizer (fig. 2) allowed to study the shape and duration of the signal produced by proton tracks. The measured signal duration was less than 2 ns, which limits the pile-up effect for incoming beam with a Poissonian distribution of particles up to 10^8 p/s on the channel.

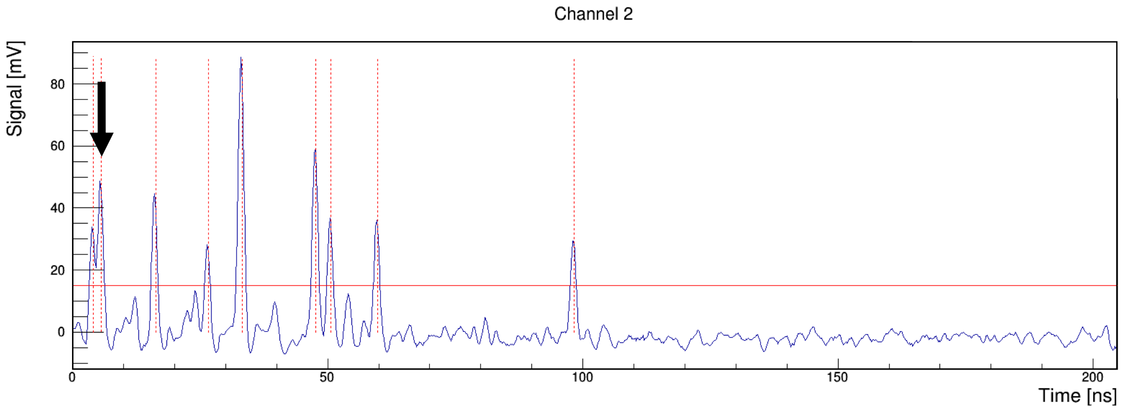

Figure 2. Example of a 200 ns time window collected with the digitizer. The arrow points at a peak with pile-up effect, while the solid red line indicates the chosen threshold to count the peaks produced by incoming particles.

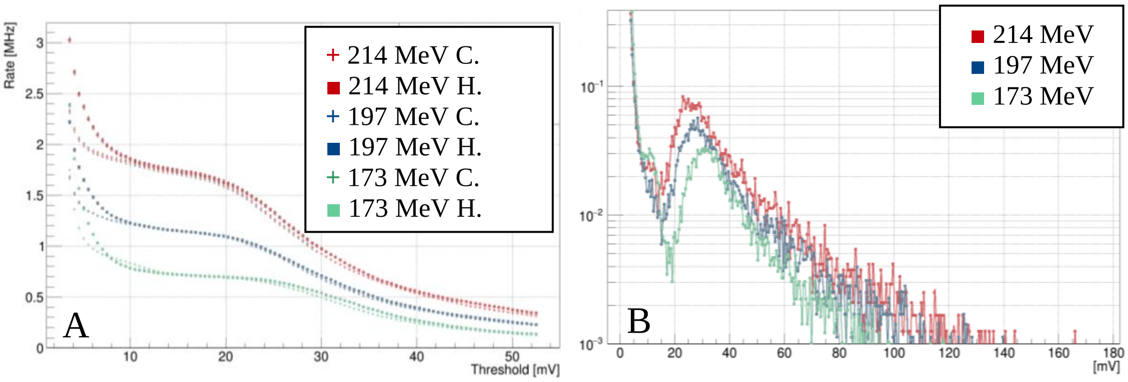

Figure 3. A. Rate versus threshold for three different energies, for both sensors (C=CNM at 250 V, H=Hamamatsu at 190 V). For low values of the threshold, a high contribution of the noise is clearly evident, while for high values of the threshold there is a significant loss of the signal. B. Amplitude distribution of the signals for three different energies for the CNM sensor, in which the vertical scale is given in arbitrary units.

To count the number of peaks, dynamic algorithms for setting the threshold on peaks amplitude were used, designed to partially distinguish overlapping signals, when possible. By deriving the rate distribution as a function of the threshold (fig. 3A), the distribution of the signal amplitude was obtained. The result is shown in fig. 3B. Because of the fluctuation of ionizations effects in a detector, the distribution is well described by the Landau formula, where, as expected, the Most Probable Value (MPV) is larger at lower beam energies because of the larger energy loss in the silicon. The amplitude distribution of fig. 3.B shows that a good separation between the noise contribution (low amplitude values) and the signal MPV can be achieved. By increasing the detector bias voltage, the MPV of the amplitude distribution can be further enhanced, improving the S/N ratio, as expected by the presence of the gain layer (fig. 4). It was proven that 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 was measured by using the charge integrated by a PinPoint dosimeter positioned behind the detectors as the reference. Several runs were acquired at different beam fluxes and the corresponding pulse rates were measured. Fig. 5 shows the measured rate as a function of the real rate as determined by the reference detector. Deviation from linearity is observed above 5 MHz.

The data were fitted to pile-up models assuming a Poissonian arrival time distribution and a fixed acquisition dead time [8]. The models were 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 fig. 2. The reason of this discrepancy originates from the highly non-uniform time structure of the CNAO beam, as observed in fig. 6, where a longer time window was acquired on the oscilloscope. A bunched structure with a frequency of few MHz was observed, probably originating from the radiofrequency of the synchrotron acceleration system. This leads to a pile-up probability larger than for uniform time distributed beam.

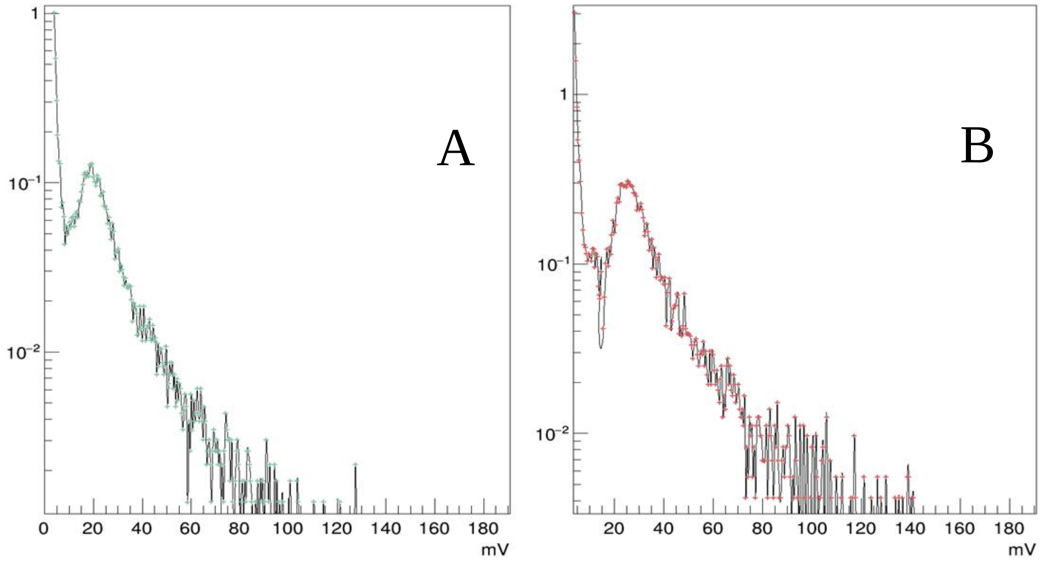

*Figure 4. Amplitude distribution for the CNM sensor with a beam energy of 227 MeV at 200 V (*A*, MPV = 20 mV) and at 250 V (*B*, MPV = 25 mV). The vertical scale is given in arbitrary units.*

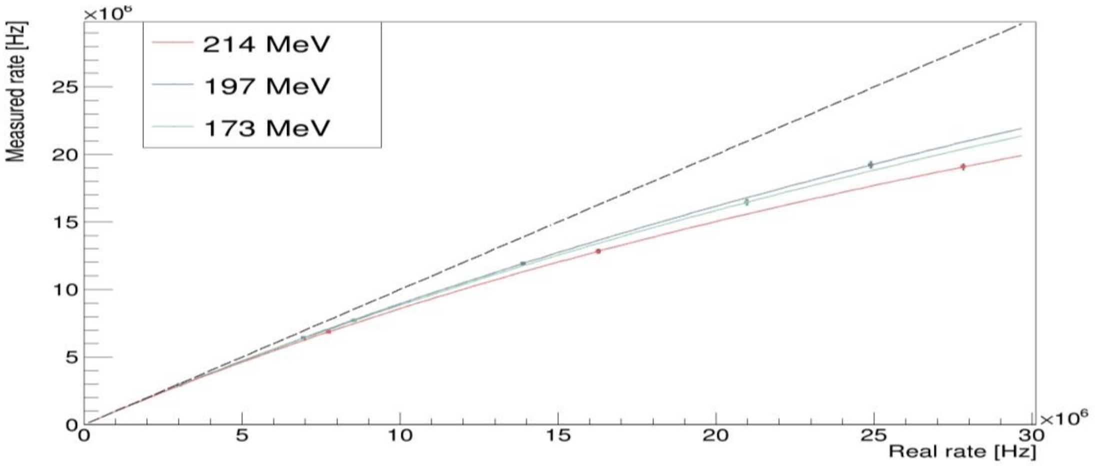

Figure 5. Measured rate as a function of the real rate estimated through the pinpoint dosimeter behind the channels. Deviation from the dashed line is caused by pile-up effects.

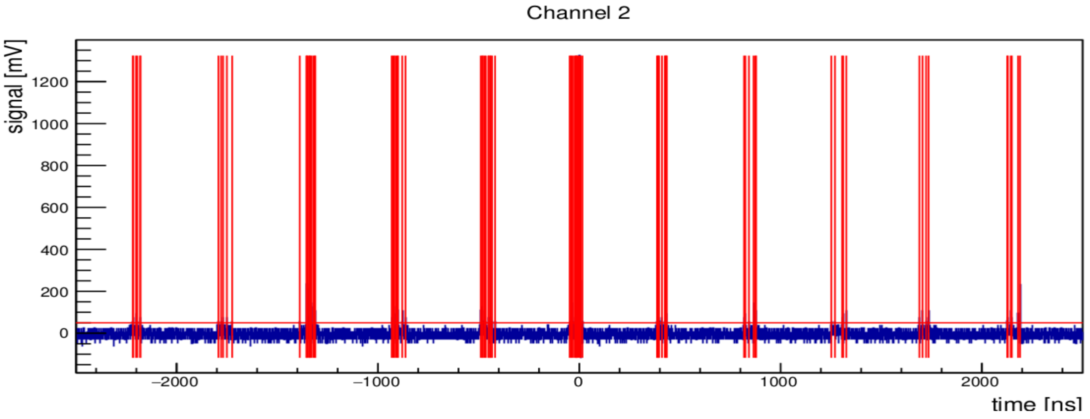

*Figure 6. A µs time window of the oscilloscope showing the bunched structure of the CNAO proton beam. The instantaneous fluence inside each bunch is ~10^{10} p/s cm^2***.**

The signals from the two sensors were found to be well correlated (fig. 7), and the distribution of the difference in time between two corresponding signals was obtained using Constant Fraction correction algorithms for each pulse in order to reduce the time walk effect. The resolution of the time difference between the pulses on the two sensors was 50 ps, resulting in approximately 35 ps time resolution for each sensor.

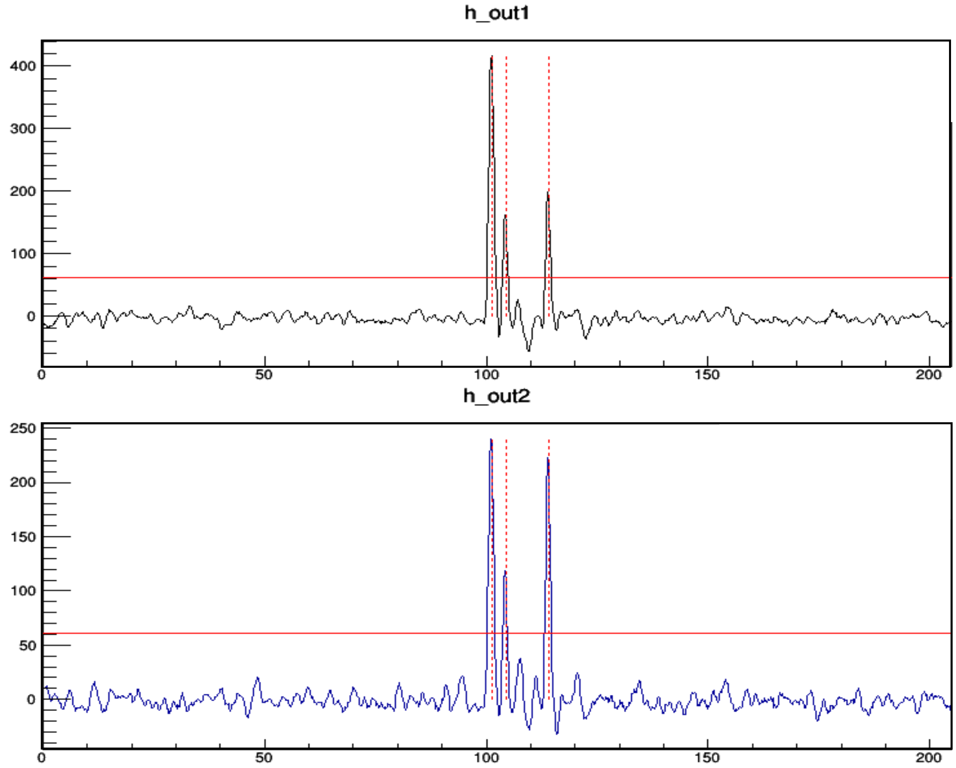

Figure 7. Corresponding time windows of the digitizer for the two sensors, showing the presence of the same peaks.

In order to determine the effect of radiation on the detector performance, the distribution of the signal amplitude for the same sensor (CNM) was compared before and after 32 runs, corresponding to about 10^{12} protons/cm^2, and a gain loss of 20% was observed, as shown in fig. 8. Similar effects leading to a loss of gain after irradiation of the sensors were observed and reported in [9].

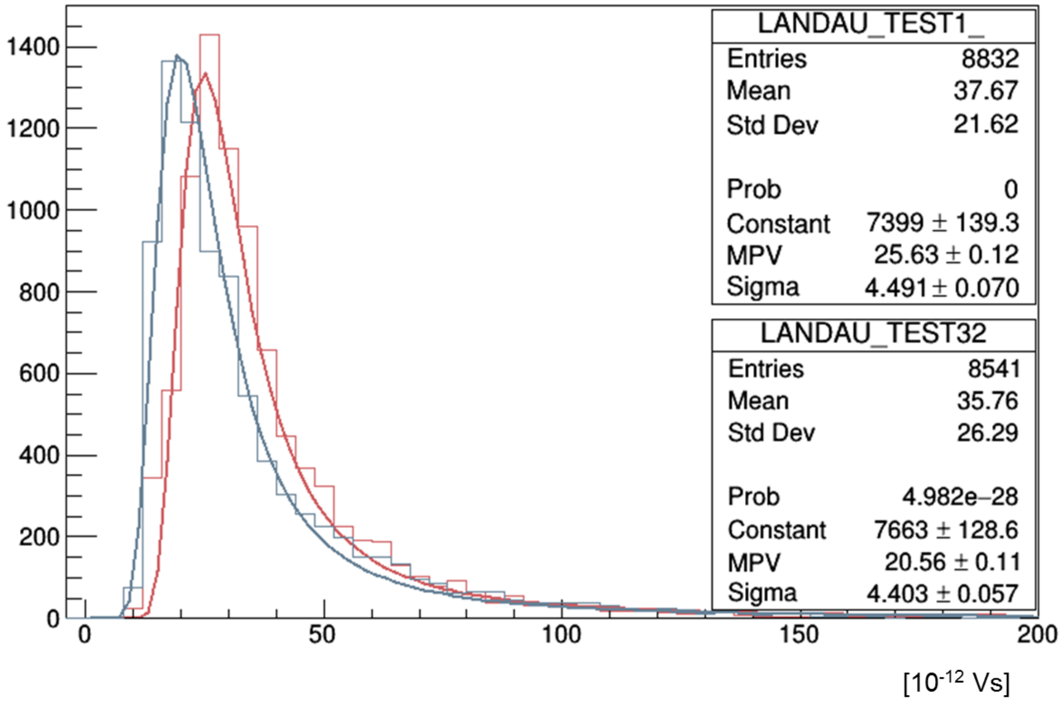

Figure 8. The MPV value of the amplitude distribution passed from 25x10^{-12} *Vs before irradiation to 20 x10*$^{-12}$ *Vs after 32 runs of proton irradiation.*

4. Future perspectives

From the results of the simulations and from the first beam tests performed with UFSD pads, prototypes of strip detectors were designed and are being produced by FBK (Fondazione Bruno Kessler) in Trento. Samples with two geometries (30 mm length x 5.6 mm width, 146 um pitch and 15 mm length x 5.6 mm width, 216 um pitch), will be available with different doping modalities for the gain layer to try to improve the radiation resistance of the device.

In parallel, the design of a new readout chip TERA10 for the sensors, featuring a preamplifier followed by a comparator with a programmable threshold, is in an advanced stage. The digital signals from each channel will be read by an FPGA implementing the particle counting and the algorithms for pile-up correction. The design goals of the new chip are rather tight. Signals out of the preamplifier should be very short, few ns at most, to reduce the signal pile-up probability. Moreover, a large input dynamic range is required considering that the charge input ranges between 3 and 130 fC. Two alternative designs, a charge sensitive preamplifier based in the TOFFEE [10] design and a differential transimpedance amplifier, both providing a LVDS output digital pulse are under investigation. Prototypes of the two chips are designed in UMC 110 nm technology and will be submitted through Europractice [11] before the end of the year.

The prototypes of detectors and readout chips will be integrated in a front-end board connected to a commercial FPGA board to allow for testing the full acquisition chain. A beam test under controlled conditions will be performed for characterizing the behavior of both the UFSD prototypes and the front-end chips as well and their integration into the full acquisition system in a realistic scenario. In addition, by varying the beam energy and the beam flux, the inefficiency induced by signal pile-up and the algorithms for the correction can be studied for different irradiation conditions.

5. Conclusions

Based on the preliminary results, UFSDs are found to be a promising alternative to monitor chambers, in particular because of time resolution of 35 ps, signal duration of ns, and good S/N separation. However, problems still need to be solved, such as pile-up effects, which can be severe in case of highly non uniform beam structures, and radiation resistance. Studies are ongoing in order to overcome these problems.

Acknowledgments

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References

[1] V. Sola et al., *Ultra-Fast Silicon Detectors for 4D tracking*, 2017 *JINST* 12 C02072

[2] N. Cartiglia et al., *Design optimization of ultra-fast silicon detectors*, 2015 NIM A 796 141-148

[3] H.-W. Sadrozinski et al. *Ultra-fast silicon detectors*, 2013 NIM A 730 226-231

[4] https://cividec.at/index.php?module=public.product&idProduct=33&scr=0

[5] http://teledynelecroy.com/oscilloscope/oscilloscopemodel.aspx?modelid=4778

[6] http://www.caen.it/csite/CaenProd.jsp?parent=14&idmod=651

[7] http://www.ptw.de/pinpoint_chambers1.html

[8] S Pommé et al., *Uncertainty of nuclear counting*, 2015 Metrologia 52 S3

[9] G. Kramberger et al., *Radiation effects in Low Gain Avalanche Detectors after hadron irradiations*, 2015 JINST 10 P07006

[10] F. Cenna et al., *TOFFEE: a full custom amplifier-comparator chip for timing applications with silicon detectors*, 2017 JINST 12 C03031

[11] http://www.europractice-ic.com/