A high rate silicon detector and front-end electronics prototype for single ion discrimination in particle therapy

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***Abstract*—The medical physics group of the Turin section of the National Institute of Nuclear Physics, on the behalf of the MoVeIT collaboration, is working for the development of a new prototype of silicon strips detector for particle therapy applications. This device, based on $50\mu m$ thin silicon sensors with internal gain, aims to detect the single beam particle and count their number up to 10^8 cm^2/s fluxes, with a pileup probability $< 1\%$. A similar approach would lead to a drastic step forward, compared to the classical and widely used monitoring system based on ionization chambers. The better sensitivity, the higher dynamic range and the fact that the particle counting is independent of the beam energy, pressure and temperature, make this silicon detector suitable for the on-line dose monitoring in particle therapy applications. The prototype detector will cover a 3X3 cm^2 area and at the moment, two sets of strip sensors with different geometry and custom design, have been produced and are currently under investigation. The classic orthogonal strip positioning is used for beam profile measures. For what it concerns the front-end electronics, the design of two different solution is ongoing: one based on a transimpedance style preamplifier, with a resistive feedback and the second one based on a charge sensitive amplifier. The challenging tasks for the design is the expected 3fC-130fC wide input charge range (due to the Landau fluctuation spreading and different beam energies), dealing with a hundreds of MHz instantaneous rate (from 200 MHz up to 500 MHz ideally). To effectively design these components, it is crucial a preliminary investigation of the sensor response to the expected stimuli. For this reason, before and during the previously cited strips manufacturing process, an extensive work has been done and is still on going, using 1.2 mm^2 area and $50\mu m$ silicon pads with gain, performing beam test at the CNAO hadron therapy center in Pavia, Italy.**

***Index Terms*—silicon sensors; front-end electronics design; particle therapy applications.**

I. Introduction

In the field of particle therapy, the typical detectors used as beam monitors are gas ionization chambers. With the aim to measure the beam flux and the beam position, a ionization chamber collects the free charges generated by ionization effects in a gas volume, confined between a couple of metal electrodes. Recently in the Turin section of the National

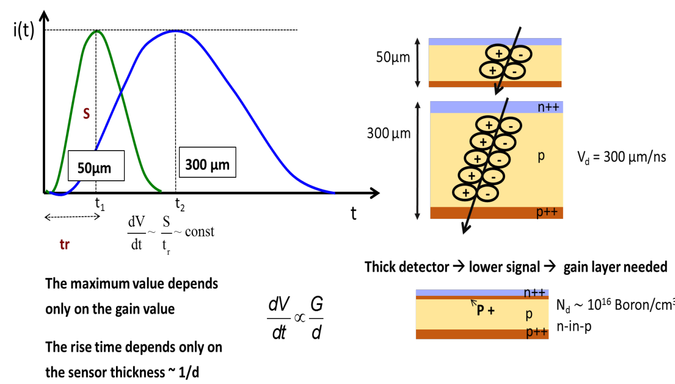

Fig. 1. Qualitative drawing representing the comparison between a classical 300 μm thick silicon sensor an a $50\mu m$ thick UFSD.

Institute of Nuclear Physics (INFN), the medical physics group is working on a new kind of silicon detectors to be put on the beam line with the purpose to count the single beam particle. This task is a MoVeIT (Modeling and Verification for Ion beam Treatment planning) work package goal. The MoVeIT project is an interdisciplinary collaboration involving various INFN groups and the three Italian hadron therapy facilities (CNAO, LNS, TIFPA), with the main purpose of developing innovative treatment planning systems (TPS) and new verification devices. The novelty in these TPSs will be the implementation of biological models, the involvement of target fragmentation, radiobiological effectiveness (RBE) and treatment of intra-tumor heterogeneity, such as hypoxia.

In this scenario, our group is in charge for the realization of a detector prototype, based on Low Gain Avalanche Diode (LGAD) type detectors, segmented in strip. The prototype has a 50 μm thickness and an extra inner silicon doped layer that provides a gain (about a factor 10-15). The scientific motivation is the fact that, combining the counting number with the charge measure provided by a classic gas ionization chamber, it is possible to find the deposited energy by a

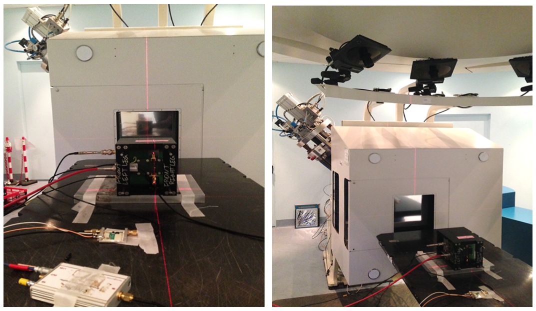

Fig. 2. Test setup at CNAO: the squared black box fixed over the treatment bed contains two PCB mounting a 50 μm thin UFSD pad each. the white device with a central metalized window is the beam monitor chamber, placed at the end of the beam extraction line.

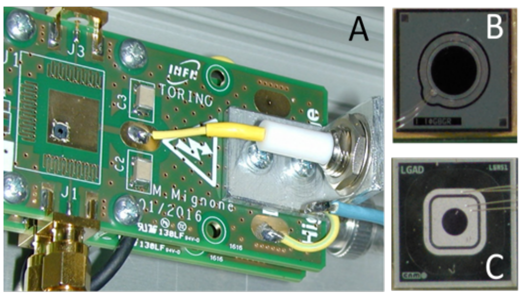

Fig. 3. A. Picture of the two sensors mounted in a metallic box and aligned to the beam. B. Hamamatsu sensor (1 mm x 50 m thickness). C. CNM sensor (1,2 x 1,2 x 50 m thickness).

single ion. In order to satisfy the 1 mm spatial resolution requirement for clinical practices, the number of particles should be measured within the 1% accuracy. This led us to the choice of thin silicon detectors, based on limited internal charge multiplication, which are able to provide a high signal-to-noise ratio in the reduced thicknesses required to have fast collection time (1 ns in 50 μm). For this feature, they are called Ultra Fast Silicon Detectors (UFSD).

II. Study of the sensor response

The UFSDs, based on the LGAD concept, are n-on-p silicon sensors featuring an internal gain due to a thin p+ and low-resistivity additional layer implanted just below the n++ electrode, providing a junction with a electric field high enough to multiply the collected charges. The layer is located closed to the bottom side of the n++ electrode of a heavily doped junction. The gain is limited to a value 10-20 in order to reduce noise perturbations and electric field confinement complexity in segmented detector configurations. Basically, the particle crossing the sensor releases charge carriers ionizing the medium. Whenever the hit occurs in the gain layer, there is a charge multiplication followed by its collection at the electrodes that is faster for thinner sensors [1] (a 35 ps time resolution for MIP particles has been observed in beam tests). The starting phase of the detector prototype realization was the simulation of the charge collection in silicon, for different shapes and dimensions of terminals and silicon layers, the doping concentration, gain and bias voltage. The Weightfield2 and TCAD Synopsys Sentaurus software are used to get an estimation of the sensor output signal features, which are critical for the front-end trade-off requests [2]. While as a first approximation the signal shape depends on the sensor thickness, the amplitude depends on the gain value and on the bulk thickness. Moving from 300 μm to 50 μm thick LGAD sensors (gain factor 10), the collection times decreases by almost one order of magnitude, from 9 ns to 1 ns. For a 50 μm thick UFSD with a gain factor of 15, a MIP particle generates a 1.2 ns signal with a charge of approximately 8 fC on average [3]. Taking into account the typical particle beam energies, we are interested in 2-6 MIP particles and a wide expected sensor signal-charge-range extending from 3-4 fC to 130 fC. A further investigation step has been performed with beam test campaigns at the CNAO particle therapy (Centro Nazionale di Adroterapia Oncologica in Pavia, Itlay) using UFSD sensors Figure 3.

III. Beam test with UFSD pads

With the aim to evaluate the counting and timing properties of UFSD sensors in a real application field, three beam test campaign has been performed at CNAO. The testing condition presented a proton beam in the 62 to 227 MeV energy range. The data acquisition took place during 32 runs of 2 10^{10} protons each, with a beam FWHM of 1 cm and a flux selection from 20% up to 100% of the maximum value. Two sensors pads of 50 μm active thickness (1,2 x 1,2 mm^2) 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 pads have been realized by the National Center for Microelectronics (CNM) in Barcelona and Hamamatsu (Japan). The sensors 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 snapshot of 200 ns duration. The setup also included a PTW PinPoint ionization chambers (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 3 shows the pad sensors used in the test. The recorded time windows of the digitizer 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 single channel. At this point, the choice of the best discrimination threshold is clearly fundamental to deal with pile up issues (Figure 6). The high resolution obtained with particle counting up to 10^9 p/cm^2s fluxes, confirm the effectiveness of a multi-channel ASIC-based systems that integrates amplification plus discrimination stages, in order to cover several square centimeters of detector area with high spatial and time resolution.

Another critical aspect related to these sensors is the radiation resistance performances. For this reason, the distribution of the signal amplitude for the same sensor (CNM) was compared before and after 32 runs, corresponding to about

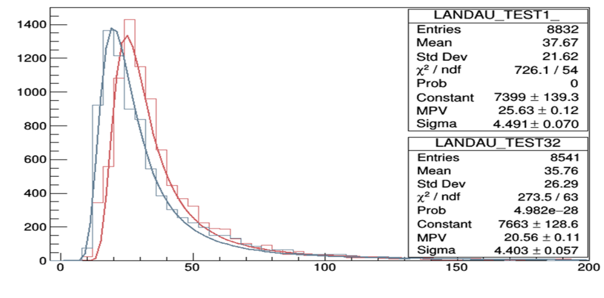

Fig. 4. The MPV value of the amplitude distribution passed from 25 10^{-12} Vs before irradiation to 20 10^{-12} Vs after 32 runs of proton irradiation

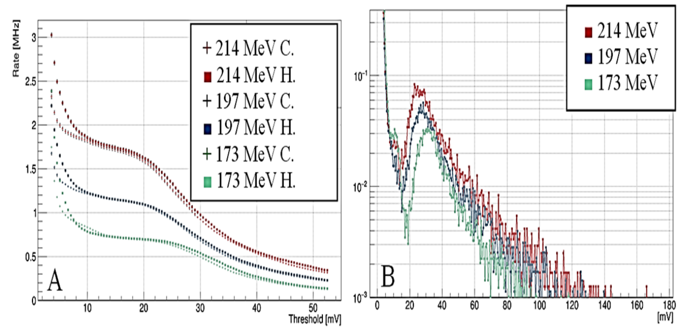

Fig. 5. A. Rate versus threshold for three different energies, for both sensors (C = CNM at 250 V, H = Hamamatsu at 190 V). For low values of the threshold, a high contribution of the noise is clearly evident, while for high values of the threshold there is a significant loss of the signal. B. Amplitude distribution of the signals for three different energies for the CNM sensor, in which the vertical scale is given in arbitrary units

10^{12} protons/cm^2; as reported in Figure 4, the out-coming information is a gain loss of 20%. Similar effects leading to a loss of gain after irradiation of the sensors were observed and reported in [8]. Although this information underlines the criticality of the problem, we already have new sensors to test with different dopant species (B, Ga, and C spray) and concentrations, suggested as being possible solutions or at lest improvements in the framework of the silicon lattice radiation damage.

IV. The silicon strip detector prototype

From the data obtained in the UFSD pad sensor beam tests and data analysis, we decided the characteristics for the beam monitor prototype silicon UFSD strips, which have been commissioned and produced by Trento (Italy) FBK (Fondazione Bruno Kessler) research center, A two sets of 50 μm thick strips, are currently under test:

30 strips 30 mm x 0.08 mm, 146 μm pitch
20 strips 15 mm x 0.15 mm, 216 μm pitch

V. CMOS design of the detector front-end

Two ASIC front-end architectures for the readout of the UFSD sensors are currently under the last phases of the design. The first approach is based on an existing chip designed by the Turin INFN microelectronic group, for the UFSD project. The ASIC, named TOFFEE [9], is a 8 channels charge sensitive preamplifier and discriminator device, optimized for timing measurement purposes in high energy physics experiments (CERN CMS-TOTEM Precision Proton Spectrometer). This chip has a NMOS input telescopic cascode, common source preamplifier, equipped with a split bias current for two independent branches with degeneration resistors for noise reduction. The signal is discriminated by a two stages comparator and feeded to a LVDS driver, in order to match a high precision TDC input levels. As previously mentioned, since the TOFFEE ASIC has been though for timing applications, it results to be not suitable for the wide input range in charge and the high dynamic range of the hits rate. The basic idea is to adapt the TOFFEE front-end for fast count operation instead of just precise timing measurement on the signal rising edge. In the new design, the preamplifier output signal needs to have both fast rising and falling edges in order to be ready to receive a following pulse. Therefore the baseline has to be recovered quickly in order to limit the peaks superposition that would lead to overlap and pile-up phenomena, Although at this point the design is only at its preliminary phase, one idea that seems to be promising at the schematic-level simulations is based on a switch transistor, controlled with the discriminator output voltage, for the reset of the integration capacitor. DAC thresholds and bias setting structures, could be included as well. The second design approach under evaluation is based on a differential transimpedance amplifier (TIA) adopting a differential cascode structure to achieve high transimpedance gain, high bandwidth, and low input referred noise, with good Power Supply Rejection Ratio (PSRR) and Common Mode Rejection Ratio (CMRR). Albeit less sensitive to low input charges with respect to the previous architecture, the TIA approach can approach the time limits given by the detector. This architecture presents a preamplifier with a relatively low open loop gain (around 10), due to the low load resistor required to have high speed. Two stages have been connected in cascade in order to increase the open loop gain and thus decrease the effect of the input capacitance. A simpler approach would have been to reduce the feedback capacitor; however, this would reduce also the close loop gain and thus increase the noise contribution of the following stages.For both solutions, a high bias current, of the order of 10 mA is needed for the input transistors to achieve high cut-off frequency and low noise. Such a high current translates in high power consumption (which is not critical in this application) and high input parasitic capacitance. The cascode structure has widely used to eliminate the effect of Miller capacitance and thus enhance the bandwidth. The ASIC prototype tape-out, is planned for the next autumn.

VI. Summary

The goal of this project is to realize a single ion discriminator for particle therapy applications. Promising experimental results on UFSDs show an excellent time resolution of 35 ps and signal duration at nanosecond with a high S/N value. Nevertheless critical aspects have to be managed from now on in order to minimize effects like pile up and radiation damage. For what it concerns the front-end electronics, we are going

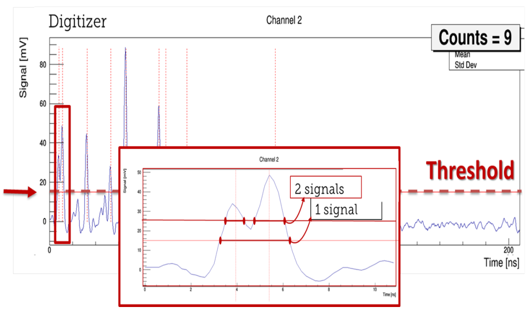

Fig. 6. Example of a 200 ns time window collected with the digitizer. The arrow points at a peak with pileup effect and the rectangular box zooms-in the area to underline the importance of the threshold selection in pileup situations.

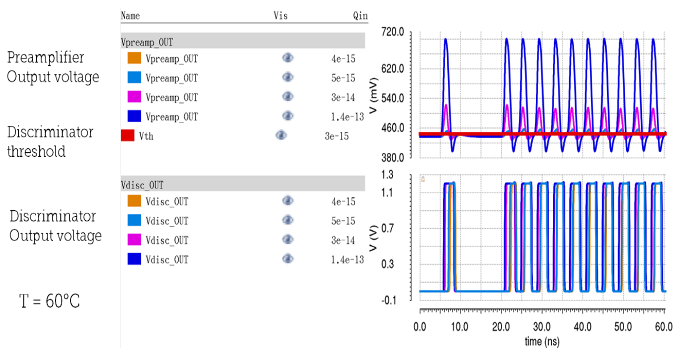

Fig. 7. Simulation results for the capacitive feedback configuration channel. The input stimulus is a single pulse coming after 5ns of delay, followed by a train of pulses with 250 MHz of repetition rate. The sweep covers the range between 4fC and 140 fC of input charge. In the upper part of the picture are represented the preamplifier output voltage and the threshold voltage for the discriminator. In the lower section is reported the discriminator output voltage.

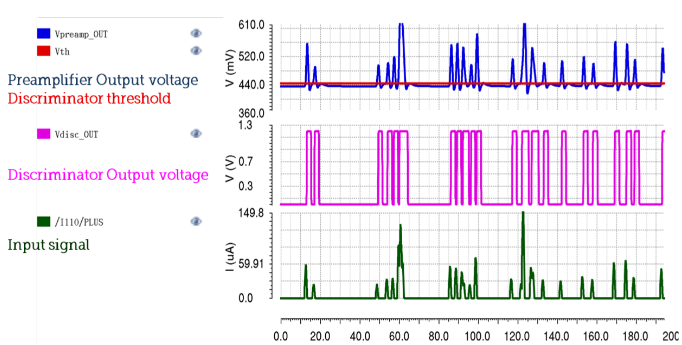

Fig. 8. Simulation results for the capacitive feedback configuration channel. In this case the input, in green on the bottom of the picture, is the result of a GEANT4 simulation for the Landau's charge distribution setting. The single input signal shape has been obtained using the Weightfield2 and TCAD softwares. In the upper part of the picture there is the preamplifier output voltage (in blue) and the discriminator threshold (in red). In the central section (in violet), the discriminator output voltage.

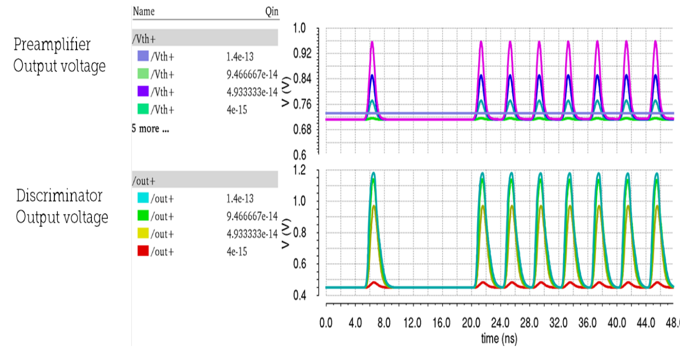

Fig. 9. Simulation results for the resistive feedback configuration channel. The input stimulus is a single pulse coming after 5ns of delay, followed by a train of pulses with 250 MHz of repetition rate. The sweep covers the range between 4fC and 140 fC of input charge. In the upper part of the picture are represented the preamplifier output voltage and the threshold voltage for the discriminator. In the lower section is reported the discriminator output voltage.

to produce two ASIC prototypes with different architectures, one based on a capacitive feedback and the second one based on a resistive feedback. Since these ultra fast silicon sensors are still rather new in the group know-how, at least from the front-end coupling point of view, the idea is to test which architecture has the best performances and then move forward with it for the design of a full ASIC (front-end plus embedded readout).

VII. Acknowledgments

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