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Characterization of a proton counter for particle therapy applications

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Summary. — A proton counter for particle therapy applications based on LGAD detectors was developed by the INFN and University of Torino.

1. – Introduction

The INFN and University of Torino are developing innovative beam monitors for particle therapy based on silicon detectors.

The state of the art of beam monitors consists of gas filled ionization chambers (IC), which measure the beam position, shape and particle flux by integrating the charge produced in the gas volume by crossing particles. Even though ICs are widely used in clinics, showing good radiation hardness, they represent a limiting factor for the development of new treatment techniques, which aim at faster and more precise delivery of the dose. The small charge produced in gases and the slow charge collection time ($\sim$100 μs) determine low sensitivity ($\sim$1000 particles) and slow response time.

Solid state detectors appear to be a promising alternative to overcome these limitations, thanks to the sensitivity to the single particles and the fast charge collection times ($\sim$ 1 ns), also allowing for the direct measurement of single particles. However, some challenges must be overcome to build a detector suitable to be used in clinics on high fluxes of therapeutic beams: the large sensitive area with 99% of accuracy, the signal pile up and the radiation damage.

This article reports the preliminary results of the characterization of a proton counter based on a planar silicon sensor, optimized to detect single protons up to a fluence of 10^8 p/(cm^{2}s) in the clinical energy range and to measure the beam profile.

2. – Materials and methods

The proton counter prototype is based on Low Gain Avalanche Diode (LGAD) sensors [1]. In order to reduce as much as possible the counting inefficiency due to pile-up,

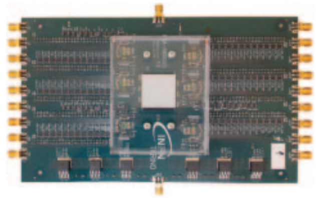


Fig. 1. – ESA-ABACUS board with LGAD sensor in the center and six ABACUS chips.

sensors with thin active thickness ($\sim 50\,\mu$m) are needed to obtain fast signals (~ 1 ns) thanks to the short charge collection time. Furthermore, fine segmentation of the sensor is also required to limit the particle rate per channel, to reduce the sensor capacitance, and to ensure a fine position resolution. The sensor for the proton counter was designed with a sensitive area of $2.6 \times 2.6\,\text{cm}^2$ to cover the beam spot, which shows a Full Width Half Maximum of about 1 cm at the isocenter. It is segmented in 146 strips with a pitch of $180\,\mu$m, each strip presents an area of $114 \times 26214\,\mu\text{m}^2$ and a gain of $\sim$10. The width of the inter-strip dead region measured in laboratory is about $80\,\mu$m [2].

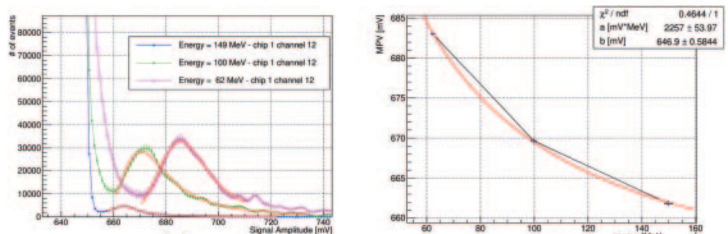
The frontend readout developed to identify signals generated by protons crossing the strips is based on a 24-channel custom ASIC, named ABACUS (Asynchronous-logic-Based Analog Counter for Ultra fast Silicon strips) [3] and designed in 110 nm CMOS technology at the INFN of Torino. Each channel features a Charge Sensitive Amplifier (CSA) designed to operate with a wide input charge range (4–150 fC), followed by a leading edge discriminator to generate a digital pulse when a signal is detected. The discriminator threshold is controlled externally to the chip and can be fine-tuned channel by channel through an internal Digital to Analog Converter (DAC), in order to compensate for the non-uniformity in the channel pedestals (DC value at the output of the CSA). The digital pulse propagated out of the chip for particle counting is also used to activate in parallel a reset circuit that discharges the feedback capacitor of the CSA and reduces the dead time of the channel. Characterization measurements reported in [3] showed a channel dead time between 5 and 10 ns, leading to a full counting efficiency up to instantaneous rates of 100 MHz or larger, depending on the input charge.

A frontend board, named ESA-ABACUS (fig. 1), was designed to house six ABACUS chips for the readout of 144 strips of the central LGAD sensor.

The output pulses of the six ABACUS chips are read out by three Kintex7 FPGA boards (KC705 evaluation board), sampling the outputs at 1 GHz and implementing a counter for each channel to store the number of 0-1 transitions. The same FPGA boards are used to set discriminator thresholds programming on board DACs. A LabVIEW program was developed to control FPGA inputs and outputs, to read counters every 100 ms and to save data for the off-line analysis.

The ESA-ABACUS board was tested at the Centro Nazionale di Adroterapia Oncologica (CNAO) in Pavia, placing the sensor at the isocenter with strips parallel to the couch plane and perpendicular to the proton beam direction. Before irradiating the sensor, the six chips were previously characterized in laboratory to set internal DACs and compensate channel pedestals.

During the beam test, the sensor was depleted with a reverse bias voltage of 200 V. Some threshold scans were performed while irradiating the sensor with proton energies in the clinical energy range, in order to select the proper threshold voltage to discriminate proton signals from noise. An example of three amplitude distributions corresponding to three different energies for the same strip is reported in fig. 2(a). The local minimum after the steep decreasing trend (due to the noise around the pedestal) was chosen as



(a) (b)

Fig. 2. – (a) Signal amplitude distributions corresponding to three energies for one strip. (b) Most probable value as a function of the beam energy for the same strip.

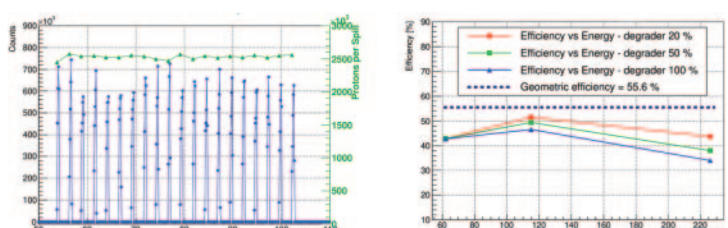
the proper threshold value to discriminate protons for each beam energy. The signal amplitude distributions were fitted with a convolution of a Landau with a Gaussian and the Most Probable Values (MPV) were plotted as a function of the energy in fig. 2(b). Since the MPV is proportional to the energy deposited in the strip, which follows the Bethe-Bloch formula, the MPV vs energy was fitted with a function $f(E) = a/E + b$, where E is the beam energy, a a parameter proportional to the gain of the CSA and b the estimator of the pedestal.

The MPV of the signal amplitude distribution for the maximum beam energy (226 MeV) is not shown in fig. 2(a) because it overlays with the noise region for most of the strips. In these conditions, setting a threshold did not allow us to efficiently discriminate the signal from noise.

In order to study the counting efficiency, different measurements with the optimized thresholds were performed using three beam energies (62, 115, 226 MeV) and three beam intensities (20, 50, 100% of the maximum beam intensity of about 5×10^9 p/s). More precisely, each run consisted of 20 spills with the same energy and intensity, requiring a fixed number of particles per spill (5×10^8 for 50, 100% intensity and 10^8 for 20%) by means of the CNAO dose delivery system.

3. – Results and discussion

Figure 3(a) reports a run with 20 spills at energy equal to 115 MeV and at maximum beam intensity: blue markers are the number of discriminated protons crossing strip number 55, while green triangles are the sum of detected protons in one spill (protons per spill) for the same strip. The beam structure with spill duration of about 1 s is well observable. The non-uniformity in time of spill shapes might be related to the non-uniformity of the particle flux within a spill, leading to counting inefficiency due to pile-up.



(a) (b)

Fig. 3. – (a) Beam structure measured with strip number 55. (b) Counting efficiency as a function of the energy for three beam intensities (degrader).

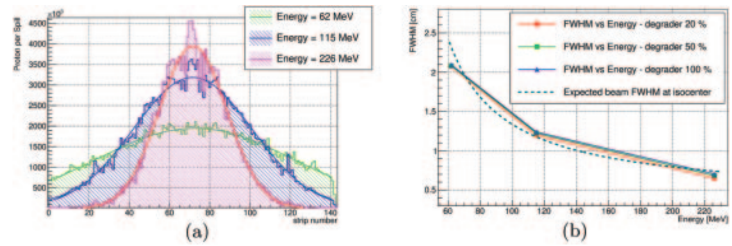


Fig. 4. – (a) Beam projections along the axis perpendicular to the strips of three spills with three energies. (b) FWHM as a function of the energy for three intensities.

The counting efficiency was computed as the ratio of the number of detected protons crossing the whole sensor in a spill and the delivered number of protons per spill. Figure 3(b) reports the counting efficiency as a function of energy compared with the geometric efficiency (computed as 1-(inter strip dead region/strip pitch)). The trend as a function of energy can be justified considering that the lower the energy, the wider the beam because of the multiple scattering in air before reaching the detector, as can be observed in fig. 4, reporting the beam projection along the axis perpendicular to the strips for the three energy values. The sensor is not large enough to cover the whole beam spot at 62 MeV, causing the lack of protons in the beam tails. The beam becomes narrower at 115 MeV leading to an increase in efficiency. The larger inefficiency at 226 MeV is mainly due to two issues: the first is related to the set threshold, which allowed us to detect only protons whose signals are larger than the threshold itself. The second one is due to the increase of the pile-up when the beam spot becomes narrower and more protons cross central strips. The pile-up effect is also evident by observing that the larger the intensity, the lower the efficiency.

Beam projections (fig. 4(a)) were fitted with Gaussians and the FWHM was plotted as a function of energy (fig. 4(b)) where it is compared to the expected FWHM [4]. The underestimation of the FWHM at 62 MeV might be due to the loss of spot tails.

4. – Conclusions

The preliminary characterization of the proton counter based on a segmented LGAD sensor proves the feasibility of directly counting protons and measuring the beam shape with a good stability in time. Inefficiency due to pile-up was observed, and further studies are ongoing to correct its effect by using two correction algorithms proposed in [5]. Furthermore, the superimposition on the noise of the MPV of the signal amplitude distribution, generated by largest energies, is under investigation to understand whether reducing the noise or increasing the gain may be possible solutions, or a new strip geometry with a different capacitance is needed.

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