A proton imaging device: design and status of realization

V. Sipala\textsuperscript{a,b}, M. Bruzzi\textsuperscript{d,e}, M. Bucciolini\textsuperscript{c,d}, G. Candiano\textsuperscript{g}, L. Capineri\textsuperscript{f}, G. A. P. Cirrone\textsuperscript{g}, C. Civinini\textsuperscript{d}, G. Cuttone\textsuperscript{g}, D. Lo Presti\textsuperscript{a,b}, L. Marrazzo\textsuperscript{c,d}, E. Mazzaglia\textsuperscript{g}, D. Menichelli\textsuperscript{e,d}, N. Randazzo\textsuperscript{b}, C. Talamonti\textsuperscript{c,d}, S. Valentini\textsuperscript{d,f}.

a) Dipartimento di Fisica, Università degli Studi di Catania, via S. Sofia 64, I-95123, Catania.
b) INFN, sezione di Catania, via S. Sofia 64, I-95123, Catania.
c) Dipartimento di Fisiopatologia Clinica, Università degli Studi di Firenze, v.le Morgagni 85, I-50134 Firenze
d) INFN, sezione di Firenze, via G. Sansone 1, I-50019 Sesto Fiorentino (FI).
e) Dipartimento di Energetica, Università degli Studi di Firenze, via S. Marta 3, I-50139 Firenze
f) Dipartimento di Elettronica e Telecomunicazioni, Università degli Studi di Firenze, via S. Marta 3, I-50139 Firenze
g) Laboratori Nazionali del Sud-INFN, via S. Sofia 62, I-95123, Catania.

**Corresponding author references**: Valeria Sipala c/o Dipartimento di Fisica, Università di Catania and INFN sez di Catania, 64, S. Sofia, Catania, I-95123, phone +39 0953785285, e-mail valeria.sipala@ct.infn.it

**Keywords**: Protontherapy, proton imaging, silicon tracker, proton calorimetry

**PACs**: 87.57.-s
Abstract –

Proton radiation therapy is a precise form of cancer therapy, which requires verification of the patient position and the accurate knowledge of the dose delivered to the patient. At present in the proton treatment centre, patients are positioned with X-ray radiography and dose calculations relay on the patient morphology and electron densities obtained by X-ray computed tomography [1]. A proton imaging device can improve the accuracy of proton radiation therapy treatment planning and the alignment of the patient with the proton beam. Our collaboration has developed a pCR prototype consisting of a silicon microstrip tracker and a calorimeter to detect the residual energy [2]. In this contribution we will show some results obtained testing the front–end board of the tracker and measurements performed at LNS (Laboratori Nazionali del Sud) and in LLUMC (Loma Linda University Medical Centre) using 60 MeV and 200MeV proton beams to test the calorimeter.
1. Introduction

The aim of the Italian PRIMA (PRoton IMAging) collaboration is to develop a proton Computed Radiography (pCR) device for application in proton therapy treatments [3]. This is the first step towards the development of a proton computed tomography (pCT) device. When a set of proton radiographs are taken from many angles, pCT can be performed in similar fashion to X-ray CT, even though the proton trajectories are not straight due to the multiple Coulomb scattering which these particles suffer when interacting with matter. The basic idea of pCT is the reconstruction of the stopping power distribution by measuring the proton energy loss along with their path through the matter. Each proton trajectory should be evaluated individually. A direct measurements of the trajectory is not possible but availability of information such as entry and exit position and direction would be an important improvement.

Monte Carlo simulations demonstrated that using this method the final pCT system should be able to measure electron density with accuracy better than 1% and with spatial resolution better than 1 mm. [3,4,5]

2. Proton Computed Radiography device

The pCR device, as shown in Figure 1, consists of a silicon microstrip tracker, to reconstruct the trajectory of each single proton, and a calorimeter to measure the particle residual energy. The tracker data acquisition is triggered by a common signal generated by the calorimeter. In order to obtain an image, the proton beam must have an energy comprised between 250 and 270 MeV, which is necessary to traverse a human torso. The tracker is made by four detecting stations (x-y planes) each one able to measure the 2 dimensional coordinate of the charged particle crossing point. A single x-y plane consists of two coupled tracker modules positioned at 90° with respect to each other. Each module is equipped with a single-sided microstrip silicon detectors. The calorimeter is made of a four scintillating crystals which are capable of stopping a high energy
proton beam. Both the tracker and the calorimeter must be able to acquire data at a maximum rate of 1 MHz to obtain a data collection time of the order of 1s.

2.1. Tracker module

Each tracker module includes of a front-end board and a digital board (see Figure 2). The front-end board contains a silicon microstrip detector with its electronic readout system. This board hosts eight integrated circuits developed for this specific application, eight buffers to drive output loads and a DAC to generate the readout chip threshold voltage. The silicon microstrip detectors were produced by Hamamatsu Photonics[6]. A sensor consists of 256 microstrips with 200 µm pitch, obtained by implanting p+ strips in a 200µm thick n-type floating zone wafer with <100> crystal orientation. The active area is 51x51mm². The chip, designed in AMS 0.35µm CMOS technology, consists of 32-channels each equipped with a charge sensitive amplifier, a shaper and a comparator which produces a digital output by comparison with an external threshold. When the sensor is crossed by a charged particle, the electronic channel, coupled with a strip, gives a digital output signal with a duration related to the charge generated in the detector and the chip threshold.

The digital board is the interface between the front-end board and the central data acquisition system. Its main purpose is to receive data from the front-end board, implement a zero-suppression procedure, store the data in a local memory device and, finally, transfer the stored data to the PC via a high speed Ethernet connection. In addition, the digital board generates test signals for even and odd electronic channels and DAC controls to set the comparator’s Vth threshold. Furthermore, it enables the calorimeter to start trigger generation and receives from the calorimeter the trigger and the GEN (Global Event Number) used for data synchronization. The digital board is based on a low-cost FPGA (Field Programmable Gate Array) with high input-output capabilities (Xilinx Spartan 3AN XC3S1400AN) and on a commercial Ethernet Unit (Memec Virtex-4Fx12 Mini Module). For each event, the Spartan-3AN read the 256 parallel lines from the eight buffers located on the front-end board and writes reduced data in a static RAM, able to acquire about $10^6$ events.
after zero suppression; then, at the end of the run, the Ethernet Unit transfers the data from the RAM to the central data acquisition PC. The communication between the RAM blocks, the Ethernet Unit and the FPGA are established through common data, address and control buses. In addition, twelve additional lines are dedicated to implement a handshaking protocol between the Ethernet Unit and the FPGA.

The first prototype of the tracker module is shown in Fig.3. The L-shaped digital board is mounted piggyback to the front-end board. Results from the ‘stand-alone’ tests of the front-end board are reported in section 3.

2.2. Calorimeter

Proton calorimetry requirements are: an acquisition rate of up to 1MHz, the ability to stop protons with high energy, high and spatially-uniform efficiency and energy resolution. Several scintillating crystal were studied in order to find the best solution for the specific application. YAP:Ce and YAG:Ce crystals were selected because they have a decay constant small enough to attain the 1MHz acquisition rate. The results of the YAP:Ce crystal [7] were promising but its maximum emission wavelength requires a photomultiplier in the readout system, which would be problematical in the magnetic field environment of a proton gantry. The YAG:Ce is more suitable to such an environment because it can be coupled to a commercially-available photodiode readout. The resulting device, therefore, is more compact and is not affected by magnetic fields [8]. The calorimeter, produced by Crytur [9] and shown in Figure 4, consists of 4 YAG:Ce scintillating crystals optically separated, 4 photodiodes and a readout electronic channels, which is made with commercially-available devices. The single crystal has a 3×3cm² cross section: the calorimeter was divided into four crystals in order to reduce the proton rate of each single crystal and to improve the resolution. Crystals depth is 10 cm which, according to a SRIM simulation [10], is sufficient to stop a 200MeV proton beam. This value was fixed considering the proton energy loss along with their path through the matter.
Four commercially-available photodiodes produced by Hamamatsu [6], with a $1.8 \times 1.8 \text{cm}^2$ area, were coupled to the crystals by an optical gel. Figure 5 shows the electronic readout system diagram: the photodiode outputs are processed with front end electronics, then sampled with an acquisition board (UF2-4032 produced by Strategic Test [11]), in order to measure their maximum amplitude. The same outputs are used to generate the trigger signal for the apparatus. The board devoted to trigger generation consists of four comparators with external threshold, a digital adder, a monostable and a counter to generate the global event number.

### 3. First results of the tracker front end board

In order to verify the measurements performed by Hamamatsu on the microstrip sensors, we tested independently the silicon detectors at our laboratory founding that their performances, in terms of leakage current and full depletion voltage, satisfy the specifications. Figure 6 shows the measurements of the leakage current of three detectors versus bias voltage. These data refer to net currents flowing through the bias ring, with the guard-ring grounded, and agree with the manufacturer data. In particular, the currents at 100V and 200V are much smaller than specifications (1uA at 100V and 3uA at 200V).

A first prototype front end board has been mounted, tested and calibrated. The voltage of the front-end chips power supply is 3.3V and power dissipation is 14.5mW per channel. The eight chips are divided into two sets, each set is fed with a common threshold. Since the chip is based on a binary read-out system characterized by one threshold, the noise of each channel was measured as a function of the threshold voltage. A noise characterized by a strong correlation between channels and induced by noise sources outside the chip was observed. Measurements from a particular chip are shown in fig. 7, where the false hits occupancy versus threshold voltage is plotted for the 32-channels and for their logic OR. The curve of the OR signal is very similar to the noisiest channel: this confirms the correlation between channels. The occupancy is defined as the fraction of time the
output pulse of a channel is high in a time interval of about 2ms, sampled at 4ns. The value 2ms for the duration of this measurement was used because it is high enough to provide a good statistics in our analysis. We determined the lowest operative threshold by imposing the condition that the false hits occupancy on every chip (logic OR of all chip channels) be less that $10^{-4}$.

By the Time Over Threshold (TOT) method, once the pulse width and the calibration curve $Q(T)$ are known, it is possible to calculate the charge released in the detector by the crossing particle. Figure 8 shows the TOT calibration obtained by injecting a charge pulse in the chip test input: at 1.69V threshold value, the output pulse width varies between 300ns ± 150ns with $1\cdot10^4$ electrons input signal and 750ns ± 20ns with $2\cdot10^5$ electrons which, according to Monte Carlo simulations, is about the most likely charge released by 30MeV protons. The width of the pulse responds to the 1MHz acquisition rate requirement.

Efficiency versus threshold voltage was measured by injecting a constant charge in the front-end chip test capacitors (Fig. 9). In these measurements the voltage threshold is high enough to make the noise induced by external sources negligible. Thus, it is possible to calculate the intrinsic noise of the single channel: in fact, the noise causes the smoothing of the transition in efficiency versus threshold curve. As marked in Figure 9, the threshold voltage interval between points at 88% and 12% efficiency, in this case about 10mV, is equal to 2.37 noise sigma. So, the noise of a single channel is about 1500 electrons, an order of magnitude less than the minimum signal expected with 250 MeV protons which, according to Monte Carlo simulations, is about $30\times10^3$ electrons. In addition, from the figure we see that the effect of dispersion of characteristics is of the order of the single channel noise. This dispersions has been accounted during data analysis since we measured the $T(Q)$ calibration curve of every channel. Anyway, the dispersion leads to an increase of the minimum threshold level which must be presently applied to the front end board.

In order to investigate the gain of the front-end chip, the minimum charge which can be detected at 99% efficiency for 32-channels at a given threshold was measured. Figure 10 shows the data
obtained for a single chip. For all the channels, the threshold can be set to detect the minimum charge released by 250 MeV protons.

The complete front-end board was tested using a $^{90}$Sr source. A low noise scintillator, located on the back of the detector, was used in order to generate the trigger signal. For each channels, pulse durations were converted into charge by inverting the T(Q) calibration curve, in order to reconstruct the charge spectrum. This distribution obtained in the case of one channel is shown in Figure 11. The data were fitted with a Landau distribution in the Moyal approximation (solid line without markers) and, in order to take into account the effect of noise, with a Landau distribution convolved with a Gaussian (open circles). The noise standard deviation has been considered a free fitting parameter. These two fitting procedures lead to the same value of most likely charge (shown in the inset for all the channels of the same chip) which is in the range $1.0-1.5 \times 10^4$ electrons, the average value being $\sim 1.2 \times 10^4$ electrons. The discrepancy between the measured most likely charge and the theoretical prediction ($1.5 \times 10^4$ electrons) is due to the non uniformity of test capacitances, whose nominal value were used in the evaluation of calibration curves.

4. First results of the YAG:Ce calorimeter

In order to characterize the YAG:Ce crystal, measurements were performed at the INFN-Laboratori Nazionali del Sud (LNS) (60 MeV maximum proton beam energy) and at the Loma Linda University Medical Center (LLUMC) (200 MeV maximum proton beam energy). The energy resolution at FWHM of the energy spectrum is 4% for 62MeV proton beam energy. Following [12] a calorimeter resolution can be proportional to the beam energy as $E^b$, with $b$ comprised between -0.5 to -1. As long as the resolution is dominated by electronic noise, it is proportional to $E^{-1}$. Otherwise, if it is dominated by scintillation statistics, it is proportional to $E^{-0.5}$. Previous tests on a small YAG:Ce crystal [8] showed that the electronic noise was dominant. We evaluated the resolution at 200MeV proton beam energy as about 1%. The four-crystal calorimeter is at an
advanced stage of testing: the energy resolution of each crystal and their optical separation were verified with 60 MeV protons at LNS. Figure 12 shows a typical charge spectrum for a single crystal, with the Gaussian fit on its peak region. The preliminary tests of crystal homogeneity were made at LNS and they show a maximum deviation of 1.2% with respect to the average value. Nevertheless, the maximum acquisition rate of this system is 1kHz. A new design for the electronic readout was chosen studied and will be developed.

5. Conclusions

The current status of a proton computed radiography device (pCR) development has been described. The tracker front end board has been completed, calibrated and tested with β particles. Results are good since it satisfies initial specifications. The tracker digital board is at an advanced stage of development. These two boards, coupled together, are going to be tested with a proton beam. The single YAG:Ce crystal has been completely characterized using a front-end electronics with commercially -available parts. A new electronic front-end with a higher acquisition rate will be implemented. The calorimeter digital board, dedicated to trigger and GEN generation, is at an advanced stage of development. New tests will be performed with the 4-crystal calorimeter to characterize the final device to be used in pCR apparatus.

References


Figures

Fig. 1. Diagram of the proton Computed Radiography device.

Fig. 2. Diagram of the tracker module

Fig. 3. Picture of a single tracker module with a front-end board and a digital board mounted piggy back.
Fig. 4. The four-crystal YAG:Ce calorimeter.

Fig. 5. Diagram of calorimeter data acquisition. The board designed to produce the trigger signal includes four comparators, a digital adder, a counter and a monostable.
Fig. 6. Leakage current versus reverse bias voltage characteristics of three microstrip detectors.

Fig. 7. False hits occupancy for the 32-channels of a single front-end chip in a time interval of about 2ms. The OR signal, being very similar to the noisiest channel, shows the strong correlation between channels.
Fig. 8. TOT calibration for the 32-channels of the front-end chip at 1.69V threshold value. The equivalent input charge was obtained with a voltage step on a test capacitance integrated into the chip.

Fig. 9. Plot of the 32-channels efficiency for different threshold voltage values at fixed input charge of 15000e⁻. The noise amplitude of a single channel and the characteristics dispersion between channels are evidenced. They are about 10mV.
Fig. 10. Plot of the minimum charge which can be detected at 99% efficiency for 32-channels at a given threshold. These data are obtained by injecting charge pulses inside test inputs.

Fig. 11. Charge spectrum of $^{90}$Sr source obtained with a single strip and a single electronic front-end channel. The experimental data (solid circles) are fitted with the Landau distribution function (solid line) and with the Gaussian convolved Landau distribution function fit (open circles). The most likely charge (MLC) for several channels is shown in the insert.
Fig. 12. Charge spectrum for a single crystal (3x3cm$^2$ cross section) with a 60MeV proton beam.