MICRO PATTERN IONIZATION CHAMBER WITH ADAPTIVE AMPLIFIERS AS DOSE DELIVERY MONITOR FOR THERAPEUTIC PROTON LINAC

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Abstract

A dedicated dose delivery monitor is under development for the TOP-IMPLART proton accelerator, the first LINAC for cancer therapy. It is expected to measure the beam intensity profile to precisely monitor the fully active 3+1D (x/y/z and intensity) dose delivery of each short pulse (few μs, 0.1-10 μA pulse current at ~ 100 Hz) of the therapeutic proton beam (up to 230 MeV). The monitor system consists of planar gas chambers operating in ionization regime with cathode plane made of micro pattern pads alternately connected by orthogonal strips. The dedicated readout electronics features trans-impedance amplifier that dynamically adapts its integrating feedback capacitance to the incoming amount of charge, then opportunistically changing its gain. The measured absolute sensitivity is about 100 fC (better than 0.03 relative sensitivity), the dynamic range up to 10000 (2 gain settings) with time response at the level of few ns, and virtually no dead time. Small scale chamber prototype (0.875 mm pitch pads) and readout electronics have been tested and characterized under both electron (5 MeV) and proton (up to 27 MeV) beams.

INTRODUCTION

According to the World Health Organization, cancers are the leading causes of morbidity and mortality; the annual cases are expected to rise by about 70% in the next 2 decades [1]. The clinical issue is exacerbated by the relevant costs of the cancer care (compare to euro 126 billion/years in European Union in 2009 [2]). Several approaches have been developed for cancer control and cure: surgery, chemotherapy, immunotherapy, radiotherapy, hormonal therapy, ultrasound therapy. Hadrontherapy, which mainly uses accelerated protons or ions, is rapidly expanding in cancers treatment, especially for the control of tumours in the proximity of vital organs or close to radiosensitive healthy organs. In fact hadrontherapy is an intrinsically highly accurate technique, due to the peculiar hadron property to release the largest amount of dose at the end of its path in the tissue while the lateral spread is small and the entrance integral dose is relatively low. Moreover the penetration in the body depends on the initial energy of the hadron. This accuracy results in effective irradiation of the tumour, thereby reducing the dose to the surrounding healthy tissues and thus leading to lower morbidity. However hadrontherapy construction and operation costs are large compared to the other therapies and this represents a serious drawback for its diffusion.

The innovative TOP-IMPLART project [3] moves in the direction of highest therapeutic impact and at the same time costs reduction by the exploitation, for the first time in cancer therapy, of a dedicated LINAC proton accelerator. Key features offered by the LINAC are the pulse current modulation (fully intensity modulated therapy), high repetition rate (better organ motion compensation), negligible power loss from synchrotron radiation (easier radioprotection), simpler injection and extraction than in circular accelerators, modular construction.

The highest conformation of the dose delivery achievable by the TOP-IMPLART requires an accurate monitoring of the beam parameters on a pulse by pulse basis; the dose delivery shall provide real-time measurements of the beam intensity profile, beam centroid position and its direction in order to guarantee that the prescribed dose is optimally delivered. The peculiar characteristics of the TOP-IMPLART LINAC[1] reflect on the following main requirements for the dose delivery monitor: good spatial resolution ~ 0.1 mm, large input dynamic range ≥ 10^4, good sensitivity ~ 100 fC, rapid response < 1 ms.

DOSE DELIVERY DETECTOR AND MULTI GAIN READOUT ELECTRONICS

The dose delivery monitor will be based on a set of 2 independent transmission ionization chambers with segmented readout planes (~ 30 × 30 cm^2 active transverse area). Design of the chamber cathode exploits recent developments in

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[1] Beam specifications: cross section ~ 1 mm, peak current 0.1–10 μA, average current 10 nA, pulse width 1–5 μs, pulse frequency 1–100 Hz.

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Micro Pattern Gaseous Detectors (MPGD) with copper pads connected by strips on both side of a thin (50 µm kapton foil) to guarantee simultaneous x and y readout; the chambers will operate in ionization region (high voltage around 200-400 V) to collect the whole ionized charge and at the same time minimize saturation effects and prevent discharge phenomena. The gap between anode and cathode will be filled by air (or mixture of inert gases) whose environmental parameters are continuously monitored (to correct for its density, mainly).

A small scale ~ 7×7 cm^2 prototype has been developed to test the main design solutions and eventually improve them. A peculiar cathode plane consisting of x and y strips (pitch of 0.875 mm with a pad-like pattern (Fig. 1) has been adopted to maximize the field uniformity (according to Garfield based analysis [4]), to reduce the overall chamber thickness (water equivalent thickness of 0.16 mm) and to obtain both coordinates on a single chamber.

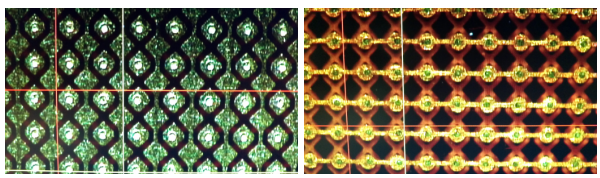

Figure 1: Detail of the layout of the cathode plane with the pad pattern; left: side exposed to the charge collection, right: external side with strips connected to the pads of the other side by filled vias.

64 out of 80 available channels on each axis are readout by a dedicated electronics able to offer high sensitivity and wide dynamic range to match the variation of the single proton pulse current during the planned treatment. The electronics basically consist of two main blocks: the input stage where each channel has a trans-impedance amplifier and a multi gain amplification logic; the output stage with a multiplexing logic that route the collected charges of the different channels into a single ADC input as well as the status information of each channel gain.

The multi gain amplification mechanism (Fig. 2) is the main peculiar aspect of the readout: as soon as the voltage on the feedback capacitor C_1 of the trans-impedance amplifier is larger than a precise voltage reference, an analog switch (driven by a latch) inserts an additional capacitor C_2, typically with $C_2 > C_1$ in parallel to the initial capacitor C_1 thus reducing the gain of the trans-impedance amplifier and therefore increasing the dynamic gain of the system. The information of the analog switch status is recorded together with the total charge on the feedback capacitor(s) related to V_{OUT}. This mechanism can be extended to several gain states; the prototype electronics consists of two gains only. A multiplexed sample and hold scheme is used, in the prototype, to read all the channels information on a single ADC.

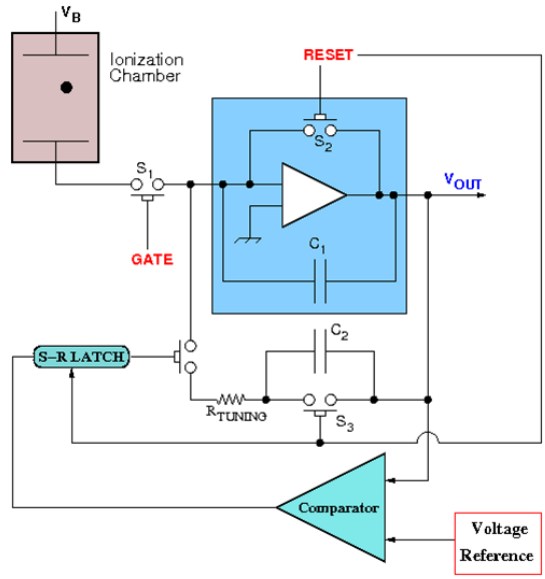

Figure 2: Schematic representation of the adaptive multi gain amplification logic.

The open box of the chamber prototype system is presented in Fig. 3, where the electronics cards are clearly visible.

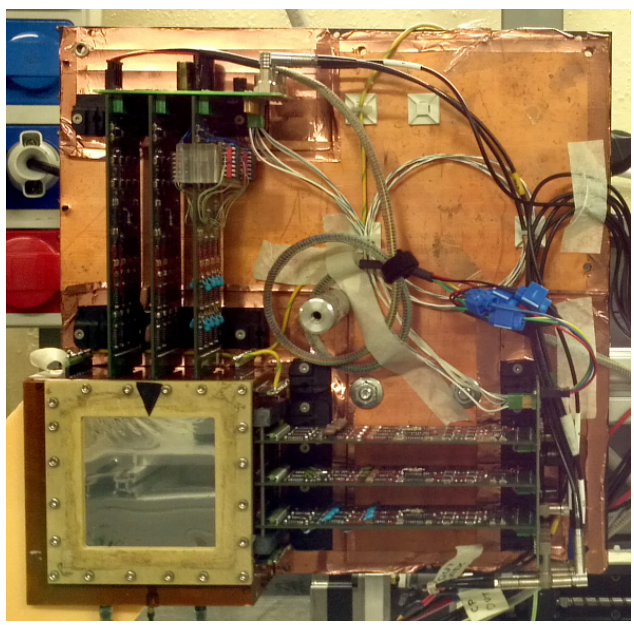

Figure 3: The small chamber prototype (bottom left) and the acquisition electronics, normally shielded by a plastic box with an internal copper layer all around, as visible behind the boards.

GAIN CHANGE CALIBRATION PROCEDURE

Each gain state has its own pedestal value which needs to be measured to correctly estimate the collected charge and then the beam intensity. While the pedestal of the first state

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is directly measured by the conventional procedure (acquisition without beam), the current electronics prototype does not include a direct mechanism to force a gain change and therefore the conventional procedure cannot be used. On the other hand a somehow electronics independent evaluation of the pedestals of the other states can be useful for a better characterization and debugging. For these reasons, a relatively simple method has been developed: assuming each channel i of the electronics at the end of a pulse e can be in one of two gain states g_i^1 and g_i^2, with $g_i^1 > g_i^2$; the collected charge $Q_i(e)$ on the strip i for a given beam pulse e is

$$Q_i(e) \propto g_i(e) \left[D_i(e, g_i) - D_i^p(g_i) \right] \quad (1)$$

where $D_i(e, g_i)$ is the ADC value of the electronic channel connected to the strip (depend on pulse e state of the channel) and $D_i^p(g_i(e))$ is the pedestal of that channel, which depends on the state of the electronics.

At the transition between the two states, the collected charge must be a continuous curve. The continuity condition can be expressed by:

$$\max_{e \in g(e)=g^1} Q(e) = \min_{e \in g(e)=g^2} Q(e) \quad (2)$$

where the strip index i has been dropped for clarity.

In fact the raw ADC values corresponding to the charge $Q(e)$ as presented in Fig. 4 does show an evident discontinuity due to the fact that the pedestals are not subtracted.

Substituting Eq. (1) in the previous Eq. (2), one gets:

$$g^1 \left[D_{max}(e, g^1) - D^p(g^1) \right] = g^2 \left[D_{min}(e, g^2) - D^p(g^2) \right]$$

which can be used to estimated the pedestal $D^p(g^2)$ of state g^2 when the corresponding pedestal of state g^1 is known (by conventional pedestal estimation, as mentioned above), and then fulfill the continuity condition.

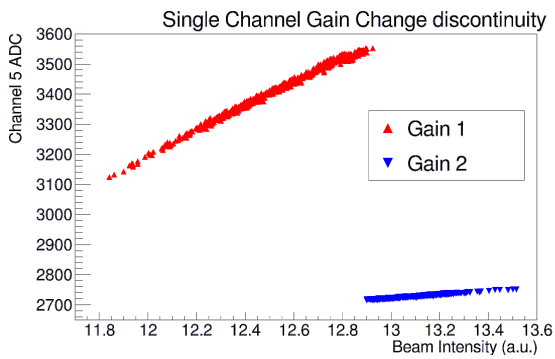

Figure 4: Collected charge (as ADC raw values) on a channel that undergoes gain changes due to the beam intensity pulse-to-pulse variations. Each point represents a pulse. The gap between the two lines of points at the discontinuity (x 12.9) is related to the pedestal of the two gain states as discussed in the text. The slopes of the lines are proportional to the feedback capacitances (referring to Fig. 2: $C_1 = 10$ pF and $C_2 = 100$ pF).

PRELIMINARY RESULTS WITH THE TOP-IMPLART PROTON BEAM

The dose delivery prototype has been preliminary tested under a 5 MeV pulsed electron beam and recently installed at the end of the TOP-IMPLART beam line which is currently able to deliver a rather stable 27 MeV beam as described in [5].

The electron accelerator had a significant level of electromagnetic induced noise; measurements in this conditions have been valuable to optimize, in particular, the signal-to-noise response of the dose delivery prototype, improving shielding and cabling complexity.

The TOP-IMPLART LINAC offers a much more electromagnetic friendly environment and the good performance of the dose delivery has immediately emerged as shown in one of the first acquisition of the beam x and y intensity profiles as function of the beam pulses, reported in Fig. 5, where the dose delivery record clean beam oscillations over pulses.

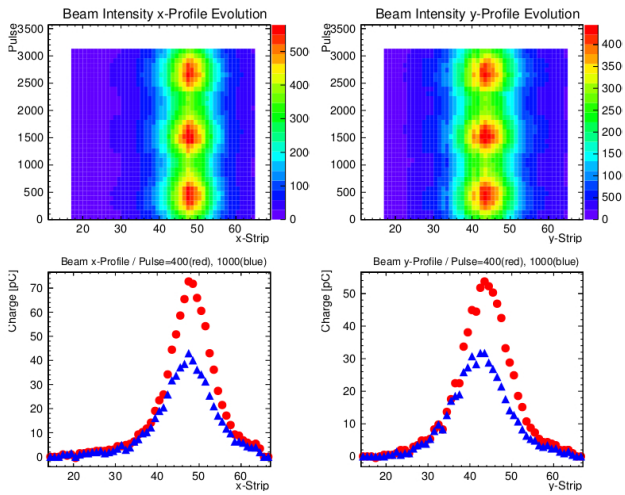

Figure 5: Example of beam transverse profile as recorded by the dose delivery prototype chamber. Top: x and y profiles versus beam pulses; bottom: x and y profiles corresponding to the highest and lowest intensity pulses. Beam frequency of 10 Hz. The beam oscillations of $\sim$ 2 min period were caused by small uncompensated temperature fluctuations in the cavities.

The single channel response equalization has been obtained comparing the beam profiles acquired at approximately 1 m from the beam pipe exit window (reference run) to the corresponding Gaussian fits (left plots of Fig. 6); the correction factors are estimated for each strip as the ratio of the fit predicted charge and the measured one (few known bad channels have been masked). These correction factors are applied to all subsequent measurements and an example of the good quality of the equalization is reported on the right plots of Fig. 6, which have been obtained in different high voltage and position respect to the reference run.

The dose delivery is currently under a preliminary dosimetric calibration by comparing its response to the response

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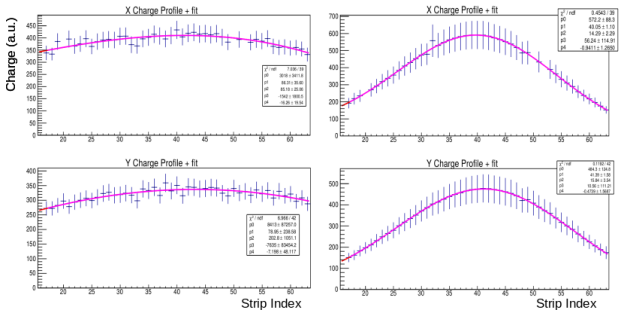

Figure 6: Equalization of the channel responses; left: profiles of the reference run used for the equalization (high voltage is 400 V); right: equalized channel responses (high voltage is 300 V, different position relative to the beam pipe exit window); the error bars represent the statistical errors and are mainly due to the beam fluctuation. The curves on top of the data are Gaussian fits. Three known faulty channels are masked in the x axis profiles.)

of small irradiated Gafchromic films and Alanine dosimeter pills. The chamber and the small dosimeters experience a different irradiation fields and their correlation need a careful evaluation. In this direction the two 1-dimensional profiles of the beam measured by the chamber have been transformed in a 2-dimensional beam intensity cross section assuming that the two x and y accumulated profiles does correspond to the respective differential profile on the single strips of the orthogonal axis; that is:

$$Q_{ij} = \frac{Q_i Q_j}{\sum_i Q_i + \sum_j Q_j}$$

where Q_i and Q_j are the charge collected on strips i and j of x and y axes respectively while Q_{ij} is the estimate charge on pixel i, j represented by the corresponding intersection of the two strips. On the other hand, the collected (or estimated) charges can be converted into local delivered dose by means of linear calibration factors, provided by the dosimetric measurements[2].

Figure 7 reports an example of the dose profiles and the reconstructed dose cross section, where the dose factors have been estimated by simple analytic considerations[3]; the obtained dose values are used as a preliminary orientation during the ongoing tests.

CONCLUSIONS

The modular design of a LINAC accelerator offers the rather unique opportunity of a concurrent exploitation of the beam during its realization, and therefore an expected

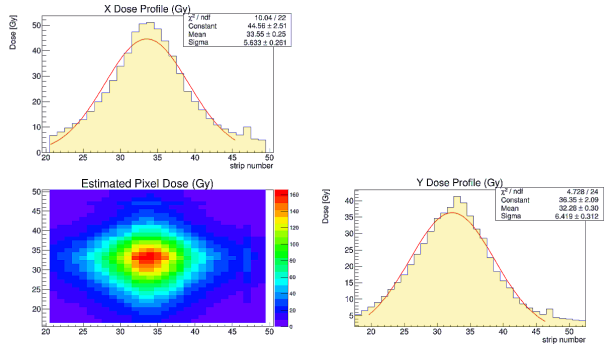

Figure 7: Beam 1-dimensional measured profiles and derived (under specific assumptions of the shape of the beam) 2-dimensional intensity cross section. The red curves are Gaussian fits of the beam profiles.

simpler commissioning and tuning of the beam itself and the components of the final therapeutic system.

The prototype of the dose delivery monitor for the TOP-IMPLART, the first LINAC accelerator dedicated to proton therapy, is under test, characterization and calibration using the currently available 27 MeV proton beam.

The preliminary results, few of them reported above, show a good response of the system, though deeper tests are underway to fully characterize key features such as the adaptive multi gain electronics as well as the saturation limit of the chamber. Possibility of an adaptive mechanism for the bias voltage of the chamber, in analogy to the multi gain electronics, is under evaluation to extend the intrinsic dynamics of the ionization regime.

ACKNOWLEDGEMENT

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[2] It is worth mention that in clinical operations the data of the calibrated dose delivery system are compared to those evaluated and provided by the treatment planning system.

[3] The dose factor for generic sensitive element k is approximately given, in the ionization regime with full charge collection, by $d_k/Q_k = w_E/(\rho_{air} v_k)$, where w_E is the effective single pair ionization energy, ρ_{air} the density of the air at the measurement conditions, v_k, probably the trickiest parameter, is the active volume contributing to the charge in k.

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