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Design and characterisation of a YAG(Ce) calorimeter for proton Computed Tomography application


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ABSTRACT: The design and the characterization of a calorimeter system, aimed at measuring the residual energy in a proton Computed Tomography (pCT) apparatus, is described. The calorimeter has a 6x6cm$^2$ active area to fully cover the tracker area of the pCT system, being 10 cm thick it is able to stop up to 200 MeV protons and sustain 1MHz particle rate (average rate on the whole area). The YAG(Ce) scintillator is promising for charged particle detection applications where high-count rate, good energy resolution and compact photodiode readout, not influenced by magnetic fields, are of importance. The aim of this work is to show data acquired with proton beam energy up to 175 MeV and to discuss the performances of this calorimeter.

KEYWORDS: Instrumentation for hadron therapy; Scintillators, scintillation and light emission processes (solid, gas and liquid scintillators); Calorimeters
1 Introduction

The use of protons for tomographic images can represent an improvement in the quality of a proton therapy treatment because of the possibility of having on-line patient positioning control and of a more accurate dose calculation, as the protons stopping power maps are measured directly. The calorimeter presented in this paper is part of a pCT apparatus, manufactured by the PRIMA (PRoton IMAging) Italian collaboration, described in [1]–[8]. The system is based on the ‘single tracking technique’, whose principle is to measure the trajectory of each proton in order to mitigate the Multiple Coulomb Scattering (MCS), which is the main limitation of the pCT application.

The proposed method attempts to:

- reveal for each proton the position and the direction upstream and downstream respect to the image volume;
- measure the proton residual energy;
- reconstruct the Most Likely Path (MLP) of the proton trajectory inside the volume to be imaged with a semi-analytic method [7, 9];
- reconstruct the irradiated image volume.

The proton trajectory is acquired using a silicon tracker (details in [1]–[8]) and the residual energy of the proton is measured by a calorimeter.

A calorimeter for a pCT applications should cope with: proton with energy up to 200 MeV, proton rate about 1 MHz, energy resolution as Full Width at Half Maximum (FWHM) equal to 1–2% @ 200 MeV.
Thanks to the scintillation light fast decay time the YAG(Ce) and YAP(Ce) crystals have been selected and studied [10, 11] for their possible use in a pCT application.

The YAP(Ce) shows better performances with respect to the YAG(Ce) in terms of maximum acquisition rate but, the YAG(Ce) crystal was chosen because its emitted light spectrum fits better with the sensitivity of the photodiode [12]. The calorimeter has to work in particle accelerator treatment rooms, where the presence of a magnetic field could be not negligible, so the use of a photodiode in the readout system is preferable to the standard photomultiplier necessary to YAP(Ce) crystal. Moreover, using photodiodes the calorimeter results more compact and permits to reduce the sizes of whole pCT apparatus.

2 YAG(Ce) calorimeter

2.1 Set-up

The calorimeter has a parallelepiped shape, $60 \times 60 \text{ mm}^2$ in section and 100mm long. A severe constraint for the pCT apparatus is the acquisition rate of 1MHz, which leads the specifications for the calorimeter geometric definition, for the electronic readout and for the data acquisition system. The calorimeter, made by Crytur [13], consists of four optically separated crystals assembled in the same housing. The longitudinal size has been chosen to stop up to a 200 MeV protons, according to the simulations made using SRIM (The Stopping and Range of Ions in Matter) software packages which calculate many features of the transport of ions in matter [14]. Each crystal was optically coupled with a S3204 commercial photodiode produced by Hamamatsu [15], which has an $18 \times 18 \text{ mm}^2$ active area with a window of epoxy resin and 0.5mm thick depletion layer. The use of a photodiode with this active area is a compromise between light collection efficiency and electronic noise (both grow with the active area).

2.2 Electronic readout

The light collected by the photodiode is converted to a charge pulse and integrated by a charge sensitive amplifier producing a voltage signal. However, the typical commercial charge preamplifiers have an output signal with a decay time constant of the order of 100 $\mu$s, which is inadequate to sustain high acquisition rates. To overcome this problem, a custom-built electronic readout has been realized. Figure 1 shows the schematic of a single read-out channel.

It consists of a fast charge sensitive amplifier with a ‘cold discharge’ mechanism, which reduces the decay time constant to about 1 $\mu$s without greatly increasing the electronic noise [16]. The high-value feedback resistor $R_F$, necessary to discharge the feedback capacitance $C_F$, comes from a non inverting low-gain (A) amplifier cascaded to the principal charge-amplifier loop. This yields a reduction of the fall time by a factor A, with no changes of $C_F$ and $R_F$ and without adding noise. Moreover the sensitivity (output voltage divided by input charge) increases by a factor A. A shaper with a 1 $\mu$s peak time is added to reduce the noise. This method allows us to detect an average particles rate of 1 MHz over the whole active area of the calorimeter reducing the signal pileup. The analog shaper outputs are sampled in parallel mode by UltraFast UF2-4032, a commercial acquisition board working at 14 bit and 50 MS/s [17]. Using this scheme the four analog channels of the calorimeter are continually sampled, with a sampling time of 200ns. For each event, a fixed
number of samples (typically 24 samples) is acquired starting from a trigger signal and the events are stored in the board internal RAM. The size of the memory is able to store 400,000 events. Offline, the pulse amplitude is derived looking at the maximum of the samples. Data analysis permits to eliminate double events (two events in the same crystal in the same time slot) or spurious and noisy events. Monte Carlo simulations show that 400,000 events for projections are enough to reconstruct a proton tomographic image, using the Filter Back Projection algorithm [6].

The trigger signal is obtained from the shaper outputs using the custom designed circuit. The four shaper outputs are sent to the acquisition board and to four discriminators which compare the analog signals with an external threshold voltage. The trigger signal is the logical OR of the four different crystal output channels. The pCT tracker can veto the trigger generator board when its read-out circuitry is busy processing a previous event [2]–[8]. In order to allow an easy and unambiguous event builder between tracker and calorimeter, the trigger signal is also used to generate a Global Event Number (GEN) associated with each event.

3 Experimental results

The calorimeter has been characterized at the INFN-Laboratori Nazionali del Sud (LNS) using the 60 MeV CATANA therapeutic proton beam line [18] and at The Svedberg Laboratory, Uppsala Sweden, with energy up to 175 MeV. Moreover, using a silicon tracker, the spatial response homogeneity of each crystal has been studied and will be discussed.

The YAG(Ce) calorimeter was positioned in front of the beam line with the beam spot focused at its center. Set of calibrated PMMA range shifter plates have been used to produce proton energy values reduced with respect to the nominal one.

3.1 Energy resolution at low energy

The raw signal amplitude distribution of each crystal in response to the nominal 60 MeV is shown in figure 2. The output signals of four channels have different amplitude, as response to a proton beam with same energy, even though the electronic front-end channels were calibrated and have the same gain. This effect could be caused by several factors: mainly the optical coupling, the photodiode intrinsic sensitivity and the crystal itself light yield.

The energy resolution values for the crystals, defined as Full Width at Half Maximum (FWHM) divided by the peak value lies between 3.5% and 5% @60 MeV.
3.2 Energy calibration procedure

In the pCT application, the calorimeter has to measure the residual energy of the single particle up to 200 MeV. Using SRIM simulator [14], the spatial spread of the beam inside the YAG(Ce) crystal was studied: with 200 MeV proton beam, a lateral spread of about 2 cm is expected. Because of the calorimeter geometry, at this energy value it is possible that a proton crosses more than one crystal. In this case, the residual energy will be the sum of the energies released in each crystal. As described in the previous section, because the channels have a different gain, the calibration is of particular importance. Measurements were performed at 60.3 ± 0.8 MeV and, using range shifter plates before the calorimeter, at 51.9 ± 0.84 MeV, 40.8 ± 1.08 MeV and 32.3 ± 1.3 MeV. Knowing the slice thickness, the proton energy and the energy spread values were obtained with GEANT4 simulations [19]. The linear light response of the scintillators to charged particles in this energy values range has been extensively reported in literature (see [20]). In agreement with the Birk’s theory at high proton energy (low stopping powers), the quenching effect can be negligible and thus, the light yield is proportional to the particle energy [20]. In figure 3, for each crystal, the amplitude output versus particle energy is plotted and the data are fitted using the simple equation \( L(E) = a + bE \) where \( E \) is the nominal beam energy, \( a \) and \( b \) are constant parameters. At low proton energy (lower than few MeV) the quenching factor have to be considered but data set does not include this energy range because is not of interest for pCT applications.

![Figure 2. Spectrum of 60 MeV protons on the YAG(Ce) crystals at LNS.](image)

![Figure 3. Crystal calibration procedure: output amplitude versus proton energy has been plotted and data are fitted using a linear curve.](image)
After the calibration procedure, the energy sum for each proton has been plotted and the resolution evaluated. At energy up to 60 MeV, the protons stop inside the crystal after maximum 1 cm with a lateral spread of about 4 mm, then a very large fraction of particles are fully contained inside one crystal. However, calculating the energy sum of the four crystals is intended to test the calibration procedure. The apparatus, in fact, will work with proton beam energy up to 200 MeV: for this energy value the later spread is higher then the single particle can through more crystals and the total energy lost is the sum of energy lost in single crystal.

Plotting the histogram of the energy sum event-by-event for the 60 MeV proton beam, the energy resolution (FWHM) is equal to about 3%. The histograms of the energy sum were produced for different energy values and the different resolutions were evaluated and reported in figure 4. The value of the resolution depends of the particle energy, as shown in figure 4. From the fitting curve used as follow [20], the expected energy resolution for 200 MeV protons is about 1%. Preliminary tests with higher energy proton beams, discussed in the 3.4 section, confirm these data.

3.3 Study of optical crosstalk between crystals

In order to test the optical separation of the four crystals, the front-end output signals were sampled in parallel mode and studied event-by-event. In figure 5 all samples, acquired in correspondence to five events (separated by the grey dashed vertical lines), are plotted. For each event 24 samples are acquired and reported in figure 5. When a proton is fully contained in a crystal, the other three signals are about zero but are sampled and acquired. Observing figure 5, in the first and the second event the proton stops inside the crystal 4. For the other events protons hit, in sequence, the crystal 2, 3 and 1 respectively.

For last event plotted in the figure 5 a signal undershoot is visible in the crystals 2, 3 and 4: this could be a cross-talk effect that leads to a wrong result for the sum in case of a shared signal. An additional data analysis has been made to understand this effect.
Figure 5. Samples of some events of 60 MeV proton beam on YAG(Ce) calorimeter. The signal amplitude has been normalised at the same value.

Figure 6. Histogram of the maximum value of each signal (24 samples) for 10000 triggers (red line); histogram of the mean value of each signal (24 samples), for the same 10000 signals fixing a software threshold on crystal 1 (blue line). The plotted data are relative to crystal 4.

Figure 6 shows, with red line, the histogram of the maximum value of each signal (24 samples), acquired by crystal 4 for 10000 triggers (10000 protons that hit the calorimeter). A logarithmic scale has been used to better highlight the tail of histogram. The maximum value of sampled signal is proportional to the energy lost by the particle in the crystal. This value is used in the data calibration procedure and in the signal sum. The histogram peak around zero corresponds with noise signals: no protons hit the crystal. The histogram peak, approximately at 2.2V, corresponds to protons that release all their energy in the crystal. Counts with amplitude values between the two aforesaid peaks are also visible.

To better investigate on the origin of these intermediate values, a software threshold to select event that hit this crystal. The threshold voltage value has been chosen considering the signal noise (about six times rms noise value). About 30% of the considered 10000 protons cross the crystal 1. In these conditions, the histogram of the maximum value of each signal (24 samples), acquired by crystal 4, is made and superimposed, for comparison, in the figure 6 using blue line.

Also in this case the histograms have a peak around zero. The undershoot signals, observed in figure 5, don’t modify the peak around zero voltage value: the mean value and the rms value are
the same. In the ideal case, when events hitting on crystal 1 are selected, the histogram (blue line) should have just the peak around zero corresponding to noise signals. However, in the mean value histogram it is also visible a peak corresponding to the most likely amplitude value: this means that in the same time windows two particles hit two different crystals. Moreover, events with amplitude value between 0V and 2.2V are visible: these could be cross-talk events but also particles that cross two different crystals. The number of counts in the tail is few with respect to the total number of counts and their contribution can be neglected. Moreover, the tail could be secondary particles delivered from the beam. GEANT4 simulations of the CATANA beam, reported in [11], show in fact a tail at low energy in the spectrum. This analysis was made for all crystals and the same results were obtained. These results permit to confirm that the cross-talk between crystals doesn’t affect the total energy evaluation.

3.4 Response to high energy protons

The YAG(Ce) calorimeter has been characterized, also, with proton beams up to 175 MeV at The Svedberg Laboratory (TSL), Uppsala Sweden. In figure 7 the spectrum of four different energies beam values, acquired by a single crystal is shown (crystal 1).

The FWHM energy resolution ranges between 2%–3% @175 MeV but the spectrum obtained with 175 MeV proton energy (blue line in figure 7) isn’t symmetric respect to the mean value. A bump, corresponding to signals with amplitude lower than the most likely value, is visible. This causes a wrong evaluation of energy resolution.

In order to understand this effect, using the pCT silicon tracker and 175 MeV proton beam, the spatial response homogeneity of the calorimeter was studied. The tracker includes two single-sided 256-silicon strip detectors, each with an area of 54 × 54 mm² [3]–[8]. For each proton the x- and y-coordinates of the trajectory impact point onto the crystal as obtained from the tracker data and the value of the calorimeter measured energy are acquired. Using the calibration procedure, an energy
A calorimeter, based on four YAG(Ce) crystals, was characterised with proton beam energy up to 60 MeV. First tests with high energy protons, were performed up to 175 MeV. The output light signal of four crystals has different amplitude, in response to a proton beam with same energy. This effect could be due to the optical coupling between crystal to photodiode, to the photodiode intrinsic sensitivity or to the crystal itself light yield. In pCT application the sum of four signals permits to know the energy lost of the particle in the calorimeter, then crystal calibration procedure is a crucial point. Tests were performed in the 30–60 MeV proton energy range, in order to fix the parameter for crystals calibration. In this energy range, the energy resolution was calculated and the resolution value at high energy was extrapolated. The optical separation between four crystals was tested and crosstalk effects were studied. First tests with higher energy proton beams confirm data
extrapolated and show good performances of calorimeter in term of energy resolution but affected by the spatial response inhomogeneity. New tests with high energy proton beams are necessary to improve the calibration procedure and to overcome the homogeneity limitation.

References


