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YAP(Ce) crystal characterization with proton beam up to 60 MeV

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Abstract

A YAP(Ce) crystal was characterized with a proton beam up to 60 MeV. Tests were performed to investigate the possibility of using this detector as a proton calorimeter. The size of the crystal was chosen so that the proton energy is totally lost inside the medium. The authors propose to use the YAP(Ce) crystal in medical applications for proton therapy. In particular, in proton computed tomography (pCT) project it is necessary as a calorimeter in order to measure the proton residual energy after the phantom.

Energy resolution, linearity, and light yield were measured in the Laboratori Nazionali del Sud with the CATANA proton beam [http://www.lns.infn.it/CATANA/CATANA] and the results are shown in this paper.

The crystal shows a good resolution (3% at 60 MeV proton beam) and it shows good linearity for different proton beam energies (1% at 30–60 MeV energy range).

The crystal performances confirm that the YAP(Ce) crystal represents a good solution for these kinds of application.

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Keywords: Calorimetry; YAP(Ce); Proton; Scintillators

1. Introduction

YAP(Ce)s are generally used as scintillators with photons in medical equipment [1,2] and environmental monitoring detectors [3] due to their high light yield, good resolution, hardness, and non-hydroscopic properties. Other well-known materials such as CsI(Tl) [4], BGO, and so on have good general characteristics and have been widely used in different experiments. Unfortunately, this kind of crystal has a slow decay time in scintillation light. This limits their high-frequency application. In this case the authors investigated the use of this crystal as a calorimeter for protons at a high rate of incoming particles.

In the proton computed tomography (pCT) project it is necessary that the crystal works at 1 MHz frequency [5].

Table 1 [6] shows a comparison between the different crystals: the YAP:Ce is between the crystals with a small decay constant. Other fast crystals, such as the LSO, LYSO, LuAP, and GSO, are tested for different applications [7–9]. In comparison with other products YAP:Ce crystal is a good compromise among general performance, cost and production capability of big size crystal.

In the pCT application it is necessary to have the crystal that stops the proton with energy until 200 MeV [10], so the crystal must be very long. By the simulations we have determined that the YAP:Ce crystal must be 10 cm long. However, the crystal has been tested with the 60 MeV proton beam in the CATANA facility. Other tests will be performed with at higher energies.

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Table 1
Properties of different well-known crystals in the physics experiment application

	BGO	CsI:Tl	YAP:Ce	LSO:Ce	LYSO:Ce	GSO:Ce	LuAP:Ce
Density (g/cm^3)	7.13	4.51	5.37	7.4	7.1	6.7	8.3
Hygroscopic	No	No	No	No	No	No	No
Chemical formula	$Bi_4(GeO_4)_3$	CsI	$YAlO_3$	Lu_2SiO_5	$LuYSiO_5$	Gd_2SiO_5	$LuAlO_3$
Wavelength of max. emission (nm)	48	550	370	420	420	440	365
Decay constant (ns)	300	900	25	42	48	30–60	18
Radiation length (cm)	1.1	1.86	2.7	1.15	1.12	1.42	1.05
Photon yield at 300 K (10^3 Ph/MeV)	8–10	52	25	27	32	8	10

2. Simulations and experimental setup

In the first instance we have evaluated the crystal–proton beam interaction. We have used the stopping and range of ions in matter (SRIM) software, which calculates many features of the transport of ions in matter [11]. For a fixed composition and density of the crystal matter ($YAlO_3$, density = 5.37 g/cm^3), and type and energy of the beam (60 MeV proton beam), this software simulates the interaction of a single proton in the YAP crystal. By this simulation we have obtained Fig. 1, where we see that all incoming 60 MeV protons are stopped in 10 mm of YAP(Ce). This value was taken into account in the light yield calculations. Moreover, in Fig. 1 we observe that the vertical displacement is around 4 mm. If the particle arrives in the region of the symmetry axis all the energy is absorbed in the medium. We have simulated a 60 MeV proton beam according to the experimental setup: in fact, we have tested the YAP crystal in the Laboratori Nazionali del Sud with the CATANA proton beam [12].

For other possible applications in the proton therapy, the crystal has be able to stop proton beams until 200 MeV [10]. We have repeated the SRIM simulation with 200 MeV proton beam to define the crystal size in order to totally absorb the energy of the incoming proton and avoid outgoing particles due to multiple scattering. After this study, we have chosen a crystal supplied by Crytur [6] with a cylindrical form, 25 mm in diameter, and 100 mm long.

We have chosen the readout system of the YAP:Ce crystal. The scintillation light wavelength is around 370 nm. It fits the maximum sensitivity of a typical photomultiplier with bialcaly photocathode. For these reasons we have used a commercial 1.2 in. PMT model 9815B from EMI. The crystal was covered with a layer of Teflon and then with 10 μm thick mylar to improve light collection. The entrance window was covered with just 3 μm thick mylar to minimize energy loss. The exit window was optically coupled to the PMT with an optical gel. The signal was acquired in charge with a 11 bit QDC. The whole electronic chain, including the PMT, was characterized with a calibrated pulsed laser. The calibration system is shown in Fig. 2. We have put the PMT in a black box and we have pulsed the PMT by the laser triggered with a pulse generator at a fixed frequency. In the single photoelectron condition we have evaluated a resolution about 0.3%.

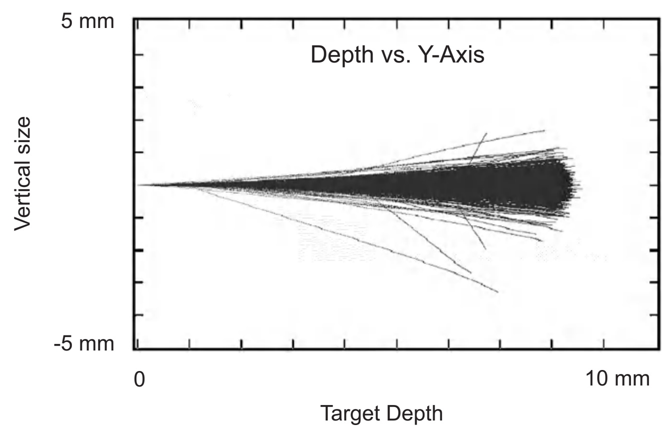

Fig. 1. The SRIM simulation of the YAP(Ce) crystal with 60 MeV proton beam.

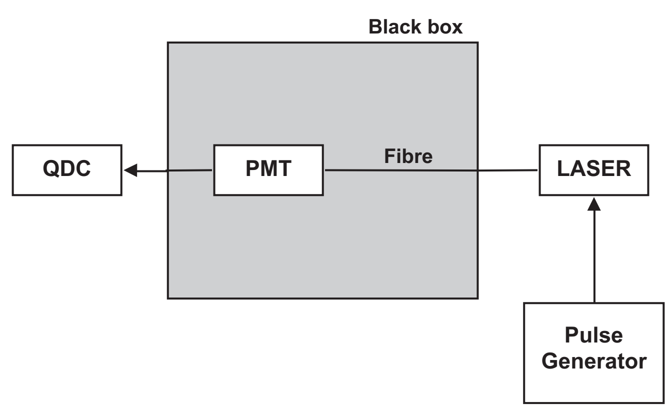

Fig. 2. Calibration system with the PMT in the black box the laser trigged by a pulse generator and a QDC used for the acquisition signal.

A test run was performed in the Laboratori Nazionali del Sud with the 60 MeV proton therapeutic beam line of the CATANA [12] equipment. A collimator with a 1 mm hole in front of the detector was used to focus the beam in the symmetry axis of the crystal. Fig. 3 shows the experimental setup used for the beam test.

In order to evaluate beam energy dispersion, due to the beam pipe window and its path through the air, the whole beam line, including the collimator was simulated. The SRIM software is not adapted to these simulations because

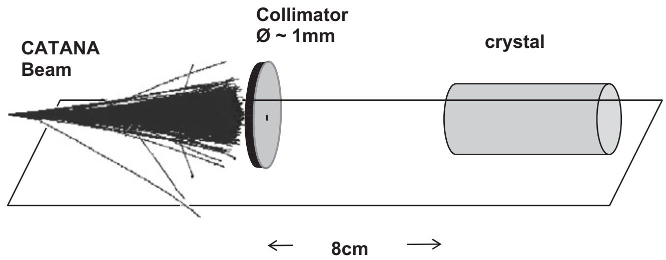

Fig. 3. Scheme of the experimental setup.

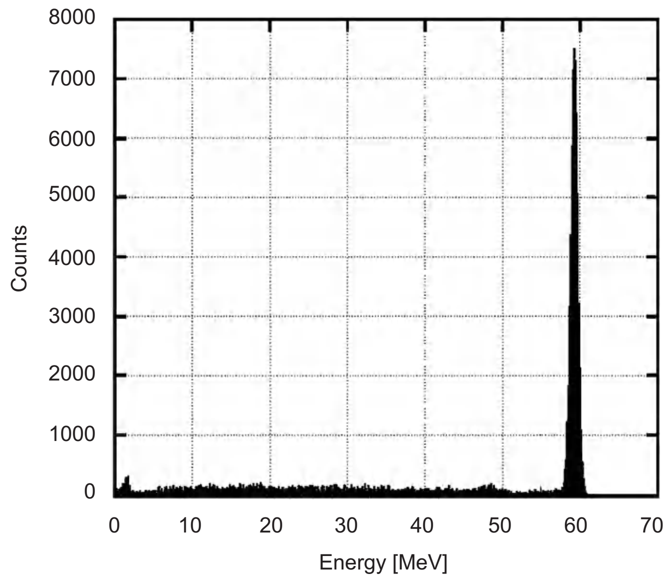

Fig. 4. GEANT4 simulated spectra.

the just explained system is complex. So the authors have used GEANT 4 [13], a toolkit for the simulation of the passage of particles through matter.

Fig. 4 shows the simulated spectra viewed by the detector. The estimated beam energy dispersion was 1.5% FWHM at 60 MeV.

3. Experimental result

The detector was installed 8 cm in front of the beam pipe. To evaluate the decay time constant of light the signal was digitized with a high performance 1 Gs/s digital oscilloscope.

Fig. 5 shows the pulse signal shape in the 60 MeV proton time domain. Assuming that the input is scintillator light described by an exponential decay, the voltage signal at the PMT anode is given by [14]

$$V(t) = \begin{cases} -\dfrac{GNeR}{\tau - \tau_s}\left[\exp\left(-\dfrac{t}{\tau_s}\right) - \exp\left(-\dfrac{t}{\tau}\right)\right] & \tau \neq \tau_s \\ \left(\dfrac{GNeR}{\tau_s^2}\right) t \exp\left(-\dfrac{t}{\tau_s}\right) & \tau = \tau_s \end{cases}$$

where G is the PMT gain, N the number of photoelectrons emitted by the cathode, e the charge of the electron; τ_s the

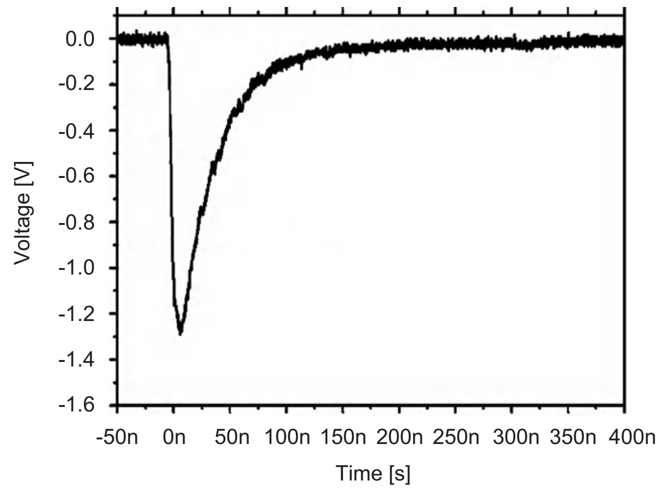

Fig. 5. PMT output signal at 60 MeV.

decay constant of the scintillator, R and C are the load resistance and capacitance, respectively ($\tau = RC$). We have fitted the output signal, shown in Fig. 5, with this equation. We know the value of PMT gain by the calibration test ($G = 5 \times 10^5$) and the load resistance ($R = 50\,\Omega$), so we obtain $N = 9.700 \pm 40$, $\tau_s = 34.6 \pm 0.2$ ns, and $\tau = 2.29 \pm 0.05$ ns. The decay constant τ_s of the crystal is very interesting for high rate calorimetry applications.

In order to calculate the light yield value of the crystal, we consider the number of photoelectrons obtained by the fit: since in the datasheet the photocathode quantum efficiency in the region of 370 nm is 30%, the number of photons in the output crystal is 32×10^3. If we consider that the 60 MeV protons are stopped in 1 cm, the photons in the crystal travel for 9 cm. The number of photons generated in the crystal depends on the radiation length of YAP:Ce (2.7 cm) and on the photon path. The light yield was estimated as 15×10^3 photons/MeV, which confirms the value supplied by Crytur.

We have written before that the overall resolution of the DAQ + PM is 0.3% FWHM at 60 MeV equivalent signal and the dispersion beam energy dispersion is 1.5% FWHM at 60 MeV. Fig. 6 shows a typical charge spectrum for 60 MeV protons: we have a resolution equal to 3%. Taking into account the initial energy beam dispersion and the electronic resolution of the DAQ system we obtain a detector resolution of 2.6%.

The same tests were performed at 30, 40, and 50 MeV. The proton beam was degraded with a PMMA slice on the beam pipe. Fig. 7 shows the detector resolution vs. proton beam energy. Fig. 8 shows the charge output signal vs. proton energy. The overall linearity in the 30–60 MeV range is about 1%.

As is well known, there are two kinds of contribution to the overall resolution in detector systems: fluctuations in signal process generation and electronic noise in readout. In the case of fluctuations in signal process generation the resolution is proportional to 1/sqr(E) where E is the particle energy loss in the crystal. In this case, the process is

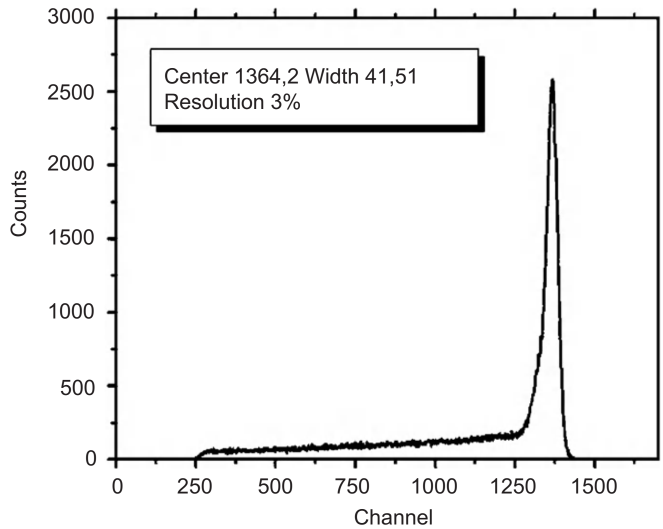

Fig. 6. Measured spectra at 60 MeV.

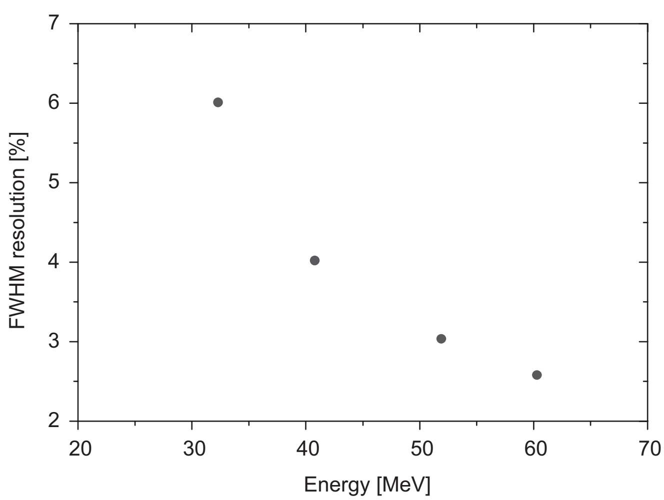

Fig. 7. Measured FWHM resolution vs. proton energy.

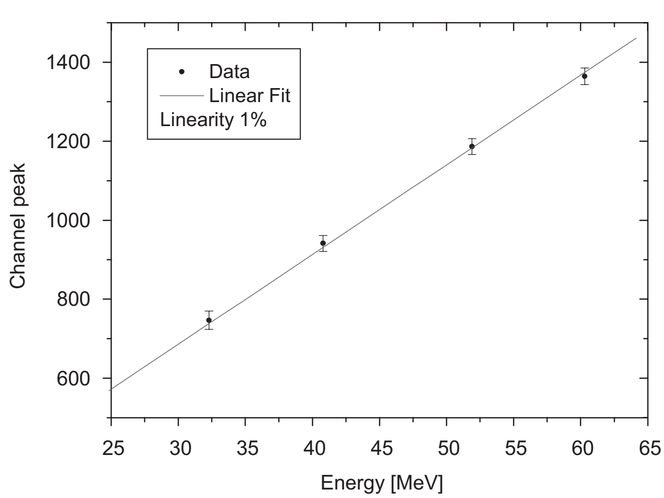

Fig. 8. Transfer function between the charge output signal and the proton energy.

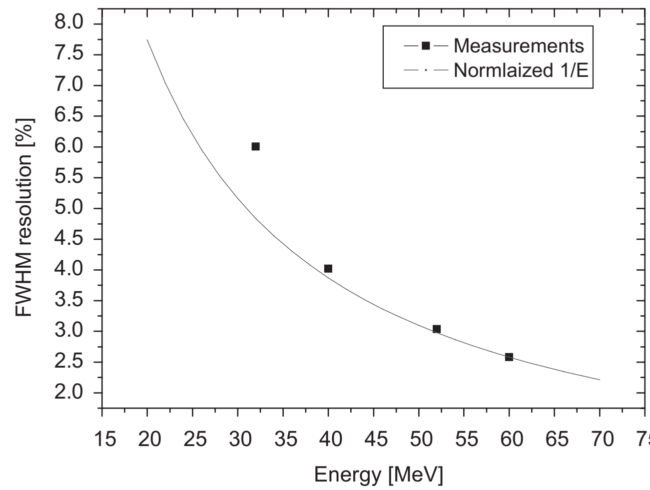

Fig. 9. Measured FWHM resolution and 1/energy curve.

Table 2
YAP:Ce summary table

Resolution at 60 MeV	2.6%
Linearity in the range 30–60 MeV	1%
Time constant	30 ns
Light yield (Ph/MeV)	15×10^{3}

the scintillation. If the fluctuations are due at electronic noise the resolution is proportional to $1/E$. We have realized a data fit and we have observed, see Fig. 9, that data are aligned to the curve $\propto 1/E$. So, our conclusion is that the contribution to the resolution is mainly electronic noise.

Table 2 presents a summary of the main characteristics of the YAP:Ce crystal used as a calorimeter with a proton beam.

4. Conclusions

A large YAP:Ce crystal was investigated with a proton beam up to 60 MeV in order to investigate its properties as a calorimeter in high-rate applications. There is a large bibliography regarding this crystal but generally they are used in nuclear medical apparatus. The high density, high light yield, and fast response makes this crystal interesting for high-rate calorimetry applications, in particular for the pCT systems.

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