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Timing capabilities of garnet crystals for detection of high energy charged particles

M.T. Lucchini[a,*], S. Gundacker[a], P. Lecoq[a], A. Benaglia[b], M. Nikl[c], K. Kamada[d,f], A. Yoshikawa[d,e,f], E. Auffray[a]

[a] CERN, Geneva, Switzerland
[b] Princeton University, Princeton, US
[c] Institute of Physics AS CR, Prague, Czech Republic
[d] Tohoku University, New Industry Creation Hatchery Center, Sendai, Japan
[e] Tohoku University, Institute for Material Research, Sendai, Japan
[f] C& A Corporation, T-Biz, Sendai, Japan

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ABSTRACT

Particle detectors at future collider experiments will operate at high collision rates and thus will have to face high pile up and a harsh radiation environment. Precision timing capabilities can help in the reconstruction of physics events by mitigating pile up effects. In this context, radiation tolerant, scintillating crystals coupled to silicon photomultipliers (SiPMs) can provide a flexible and compact option for the implementation of a precision timing layer inside large particle detectors. In this paper, we compare the timing performance of aluminum garnet crystals (YAG: Ce, LuAG: Ce, GAGG: Ce) and the improvements of their time resolution by means of codoping with Mg^{2+} ions. The crystals were read out using SiPMs from Hamamatsu glued to the rear end of the scintillator and their timing performance was evaluated by measuring the coincidence time resolution (CTR) of 150 GeV charged pions traversing a pair of crystals. The influence of crystal properties, such as density, light yield and decay kinetics on the timing performance is discussed.

The best single detector time resolutions are in the range of 23–30 ps (sigma) and only achieved by codoping the garnet crystals with divalent ions, such as Mg^{2+}. The much faster scintillation decay in the co-doped samples as compared to non co-doped garnets explains the higher timing performance. Samples of LSO: Ce, Ca and LYSO:Ce crystals have also been used as reference time device and showed a time resolution at the level of 17 ps, in agreement with previous results.

1. Introduction

The capability to precisely measure the time of interaction of ionizing particles using radiation detectors is becoming a crucial aspect in medical imaging and high energy physics experiments. A detector with a time resolution at the level of tens of picoseconds would allow to improve image reconstruction in positron emission tomography (PET) scanners [1–4] and would permit to mitigate the effects of event pile up in high luminosity collider detectors, which operate under high rate conditions [5]. Previous studies demonstrated the capability to achieve sub-20 ps time resolution using devices consisting of L(Y)SO:Ce and LSO: Ce, Ca crystals read out with silicon photomultipliers (SiPM) [6]. In this context, LSO:Ce and LYSO:Ce crystals represent excellent candidates for timing applications due to their high light yield (40000 ph/MeV) and relatively fast decay time (40 ns). In addition, it has been shown that Ca^{2+} codoping improves the scintillation characteristics of Ce-doped LSO by suppression of slow delayed recombination processes with consequent decrease of the scintillating decay time down to 31 ns [7,8]. Similar and very encouraging studies have recently demonstrated the possibility to improve the scintillation properties of aluminum garnet crystals, such as YAG: Ce, LuAG:Ce and GAGG: Ce, by codoping with Ca^{2+} and Mg^{2+} ions [9–11]. The faster scintillation pulses achievable in such codoped crystals make them an attractive and promising option for timing applications. In particular, GAGG:Ce crystals show a light yield higher than LSO:Ce and good timing has already been measured for Mg-codoped samples using low energy γ-rays despite the slower scintillation time profile [4,12]. As aluminum garnet crystals have also been proven to be extremely radiation tolerant to high levels of ionizing radiation and hadron fluences they can operate in harsh radiation environments such as those of future hadron

* Corresponding author.
E-mail address: Marco.Toliman.Lucchini@cern.ch (M.T. Lucchini).

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colliders [13]. In this paper we investigate and discuss the improved timing capabilities of garnet crystals codoped with Mg^{2+} ions (YAG, LuAG, GAGG), for high energy physics applications. Timing results obtained with LYSO:Ce and LSO: Ce, Ca crystals used as reference time detectors are also discussed. An overview of the optical and scintillation properties of the crystals is also given and discussed in relation to the timing performance achieved for detection of 150 GeV pions.

2. Experimental methods

2.1. Crystal samples

Six different Ce-doped garnet crystals have been used for this test: one LuAG: Ce, one YAG: Ce, one GAGG:Ce and the corresponding samples codoped with Mg^{2+} ions (i.e. LuAG: Ce,Mg, YAG: Ce,Mg and GAGG: Ce,Mg). Two pairs of $2 \times 2 \times 5$ mm^3 and $2 \times 2 \times 10$ mm^3 LSO: Ce, Ca produced by Agile and one pair of $6 \times 6 \times 3$ mm^3 LYSO:Ce crystals from CPI [14] have also been measured for comparison and to provide a reference time detector for coincidence time resolution measurements.

The Garnet crystals were grown by Czochralski method at a speed of about 1 mm/hour and using an iridium crucible under N_2. For the GAGG samples, the seed crystal of ⟨100⟩ orientation was purchased from C & A Corporation, Sendai, Japan. Mixtures of oxides of purity 5N with compositions of $Gd_{2.982}$:$Ce_{0.015}Ga_{2.7}Al_{2.3}O_{12}$ and $Gd_{2.982}Ce_{0.015}$ $Mg_{0.003}Ga_{2.7}Al_{2.3}O_{12}$ were used as starting materials. For the YAG and LuAG samples a stoichiometric mixture of 4N $MgCO_3$, CeO_2, a-Al_2O_3, Y_2O_3 and Lu_2O_3 powders was used as starting material. Nominally, starting powders were prepared according to the formula of $(Mg_{0.005}Ce_{0.0005}$ $Lu_{0.99})_3Al_5O_{12}$ and $(Mg_{0.005}Ce_{0.0005}$ $Y_{0.99})_3Al_5O_{12}$ and seeds of ⟨111⟩ oriented YAG crystals were used. All crystal were then cut to dimensions of $2 \times 2 \times 10$ mm^3 with the two end faces polished. The lateral faces were also polished for the reference samples and GAGG but not for the YAG and LuAG samples.

The scintillating properties of the samples, summarized in Table 1, were measured in laboratory using the same instrumentation and procedure described in [12]. The light yield was measured using a ^{137}Cs source, wrapping the samples in several layers of Teflon and coupling them to a Hamamatsu Photonics R2059 photomultiplier tube (PMT) with optical grease (refractive index n=1.41). The decay time measurements were performed using time correlated single photon counting [15], in which the start-detector is realized with a $2 \times 2 \times 5$ mm^3 LSO:Ce codoped 0.4% Ca scintillator coupled to a Hamamatsu S10931-050P SiPM and read out by the NINO chip [16]. The stop-detector was realized with a single photon avalanche diode of 50 μm (ID-Quantique ID100-50) as discussed in [17]. A double-exponential fit was performed to estimate the decay time components according to the following parameterization,

$$A(t) = A_1 e^{-t/\tau_{d,1}} + A_2 e^{-t/\tau_{d,2}}$$

in which the relative intensity of the two components, in terms of total number of photons emitted, is given by

$$I_i = \frac{A_i \tau_{d,i}}{\sum A_i \tau_{d,i}}$$

The Mg^{2+}-codoped samples show a faster decay time due to the stabilization of the Ce^{4+} centres, which provide an alternative channel for fast radiative de-excitation and thus compete with any kind of electron traps in the material for the capture of an electron from the conduction band [12,18].

2.2. Experimental setup

The crystal samples were wrapped with several layers of Teflon as reflector and glued to a 3×3 mm^2 Hamamatsu S13360-3050PE SiPM using Meltmount glue with refractive index n=1.68. For the $6 \times 6 \times 3$ mm^3 LYSO:Ce crystals, larger area SiPMs were used (HPK 6×6 mm^2). The single cell size for both SiPMs is 50 μm, the photon detection efficiency (PDE) has a maximum of 55% at 430 nm when operating bias voltage was set to about 9 V overvoltage ($V_{br} \approx 52$ V). The signal from the SiPM was read out using a customized board providing a fast time signal obtained with the NINO chip and the amplified analogue waveform as described in [22]. The signals were read out with a CAEN V1742 module, providing a fast digitization of up to 32 channels at 5 GS/s. Three NINO boards, instrumented with two SiPMs each, were used in parallel to allow the simultaneous measurement of 6 crystal samples as shown in Fig. 1. The boards were aligned with a mechanical support and placed inside a thermally isolated, light tight box with stable temperature of 15 ± 0.5 °C.

The same operating voltages for the NINO thresholds were applied to all the boards and the same bias voltage of 61.5 V was applied to power the 3×3 mm^2 HPK SiPMs (corresponding to about 9 V overvoltage). The larger 6×6 mm^2 HPK SiPMs used for the LYSO:Ce crystals were operating at 61 V (9 V over breakdown voltage).

A pion beam of 150 GeV momentum was provided by the H2 beam line at CERN which allows a precise selection of particles in the 10–250 GeV energy range by means of several magnets and collimator elements. High energy pions traversing a 10 mm long crystal have a small probability (~3%) to interact via inelastic scattering and produce large energy deposits inside the crystal. In the majority of cases the pions will cross the whole crystal thickness depositing an energy close to the value of a minimum ionizing particle (mip), i.e. about $k\rho$ MeV/cm where ρ is the density of the compound (reported in Table 1) and k an empirical coefficient with values ~1.57 for YAG and ~1.48 for LuAG, GAGG and LSO. As a pion goes through the setup, it creates a signal in all the crystal samples aligned in the box. The time stamp of each channel is computed at the 50% of the corresponding NINO output

Table 1
Summary of crystal dimensions and density for the samples used in this study. Optical and scintillation parameters as measured in laboratory are also reported: decay time components ($\tau_{d,i}$) with relative intensity (I_i), light output measured using a PMT R2059 and ^{137}Cs source. Values for reference crystals are also shown for comparison and were measured in [17]. The values of refractive index are taken from literature [19–21].

Dimensions [mm^3]	Crystal type	Density (ρ) [g/cm^3]	Refractive index at 500 nm	$\tau_{d,1}$ [ns]	I_1 [%]	$\tau_{d,2}$ [ns]	I_2 [%]	LO [ph/MeV]
2×2×10	YAG:Ce	4.6	1.84	102	52	492	48	13000
2×2×10	YAG:Ce:Mg	4.6	1.84	59	84	225	16	17000
2×2×10	LuAG:Ce	6.7	1.86	98	33	1907	67	9000
2×2×10	LuAG:Ce:Mg	6.7	1.86	50	86	908	14	14000
2×2×10	GAGG:Ce	6.6	1.92	101	65	319	35	34700
2×2×10	GAGG:Ce:Mg	6.6	1.92	51	53	196	47	26700
6×6×3	LYSO:Ce	7.1	1.81	24	15	45	85	27000
2×2×5	LSO: Ce, Ca	7.4	1.81	8	6	33	94	22200