Investigation of Cherenkov radiation component in LYSO(Ce) crystals

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Abstract. The fast scintillation crystals such as pure CsI or LYSO(Ce) today are considered for timing measurements in future colliding beam experiments. The aim of such counters is to determine time of particles arrival with accuracy better than 100 ps. The work is devoted to investigation of influence of Cherenkov radiation on the time resolution of the detectors based on LYSO(Ce) crystals. The results of MC simulation and beam test are presented.

1. Introduction

In present does not exist systems for measurement time of particles arrival with accuracy better than 50 ps [1, 2]. The development of a time-of-flight system with a time resolution better 100 ps will open new horizons for using this technique in colliding-beam experiments. This will allow to suppress the effects associated with the pileup of events from different vertex. Perform $\pi/K/p$-separation with high reliability over a wider range of momentum. The fast scintillation crystals such as pure CsI or LYSO(Ce) today are considered for such timing measurements. LYSO(Ce) crystals are fast (60 ps rise, 40 ns decay), bright (40000 ph/MeV) and enough radiation hard. In this paper we consider the construction time-of-flight counter consist from LYSO(Ce) crystal read-out with silicon photomultiplier (SiPM). Future barrel part MIP Timing Detector (MTD) of the CMS detector will be based also on such assembly [3]. The expect time resolution for MTD better than 30 ps. The Cherenkov photons could be a reason of an additional jitter or systematic shift of signal arriving time from different ends of the bar. We estimate the effect of the Cherenkov radiation in LYSO(Ce) crystals on its timing properties with simulation and beam test experiment.

2. Geant4 simulation

2.1. Detector construction

The simulation in Geant4 framework performed for the detector construction shown on Fig. 1 [4]. The LYSO(Ce) bar have 4.5×4.5×50 mm sizes. The scintillation light and Cherenkov radiation are detected with help of two SiPMs which have the sensitive area 3×3 mm. The SiPMs are coupled to crystal through optical grease ($n=1.56$). The first SiPM located in endcap position and second SiPM in the forward direction to particle gun.
2.2. Data for G4 simulation

All results for simulation were obtained with maximal quantum efficiency of SiPM (Fig. 2). The refractive index and transmittance in dependence from wavelength for LYSO(Ce) shown on Fig. 3. Fig. 4 demonstrate the LYSO(Ce) scintillation and Cherenkov emission spectra.

2.3. Optical photons time spectra

Time distribution of photoelectrons produced in SiPM2 located in forward direction to particle gun by 5000 electrons with energy 2.5 GeV shown on Fig. 5. In first 100 ps detected about by 6 Cherenkov photons.

The angle between Cherenkov photons and track of particle determined through the formula $\cos(\theta_{ch}) = (\beta n)^{-1}$, where $\beta = \theta/c$ and the LYSO(Ce) refractive index $n=1.82$ ($\lambda=445$ nm). We considered three situation with rotation the LYSO(Ce) bar relatively to position particle gun:
Figure 5. Time distribution of photoelectrons for Scintillation and Cherenkov signals.

- the perpendicular – $\theta_{ch} \simeq 57^\circ$ and Cherenkov radiation captured in total internal reflection ($n \times \sin \theta_{ch} > 1$) and go to both endcaps;
- -30° from perpendicular – Cherenkov radiation go to right endcap where absent SiPM;
- +30° from perpendicular – Cherenkov radiation go to left endcap where located SiPM1.

For all cases particles hit to the center of the SiPM2. Some small part cherenkov radiation hit in side faces the LYSO bar and go to both endcaps. The results with time distribution of photoelectrons for the Scintillation and Cherenkov signals shown on Fig. 6. The Cherenkov photons arrival time is shifted up to 30 ps for different angles between particle track and crystal.

Figure 6. Time distribution of photoelectrons for Scintillation and Cherenkov signals for different positions: perpendicular, -30° from perpendicular and +30° from perpendicular respectively (from left to right).

3. Experiment
3.1. Beam test facilities at BINP
The experiment was performed with the electron test beam facility of VEPP-4M electron-positron collider at Budker Institute of Nuclear Physics (BINP) [5]. A special probe is moved into the halo of a primary electron beam of the VEPP-4M collider for generation of Bremsstrahlung gammas (see Fig. 7). These gammas are converted to electron-positron pairs on a lead target at the entrance to the experimental hall. Electrons with a certain momentum are selected by using a bending magnet. Electron beam energy is tunable up to 3.5 GeV and intensity is 50÷100 Hz.

3.2. Scheme of the experiment
In the our experiment electrons with 2.5 GeV energy were used. The scheme of the experiment is shown in Fig. 8. Particle tracking was performed by two gas electron multipliers (GEM) with intrinsic resolutions $\sigma_x \sim 70 \mu m$ and $\sigma_y \sim 200 \mu m$ installed with about 1 m distance between
Each other. As a trigger for the data acquisition system the coincidence of the signals from MCP-TRG1 and MCP-TRG2 based on photomultiplier tube with micro-channel plates (MCP-PMT) with Cherenkov radiator (plexiglas round tablet optically coupled to the photocathode) before and after tested bar was used [6, 7]. For waveform digitization of the signals, over 200 ns, a 12-bit 5 GSample/s switched capacitor digitizer (CAEN-V1742) was used. The LYSO(Ce) bar read out from one endcap MCP-PMT and with forward SiPM Hamamatsu \((3\times3 \text{ mm})\). The LYSO(Ce) bar \((3.5\times4\times50 \text{ mm}, \text{ covered by PTFE})\) placed respect to beam line at the perpendicular, \(+30^\circ\) and \(-30^\circ\) from perpendicular position. For each configuration \(~100 \text{ kevents}~\) were collected in June 2019.

3.3. Test beam results

The Fig. 9 show applied cuts for selection tracks. NaI-calorimeter and MCP-PMTs amplitudes cuts are applied to select single particle events with straight tracks. For choice tracks hit in the SiPM area on the LYSO bar the GEM information used and we applied cut on amplitude SiPM.

The typical waveforms of the signals from trigger counters, endcap MCP-PMT and forward SiPM are shown in Fig. 10. For more accurate time determination we use linear approximation of
pulses front edges. The time of the signals is determined at the level of 50% and 30% amplitude magnitude. For SiPM we have saturation in the signal and fit apply for rising front only.

The distribution of the time difference ($\Delta T$) between the signals from the trigger MCP-PMT and the reference detector (MCP-PMT or SiPM) is used to determine a time resolution. The typical $\Delta T$ distribution for the MCP-PMT and SiPM is shown in Fig. 11. The $\sigma$-parameter of the gaussian approximation for this distribution is quoted as the time resolution.

The Fig. 12 show dependence time resolution and mean value $\Delta T$ on the angle of rotation of the crystal to beam line between MCP-PMT and SiPM for different thresholds.

4. Summary
The Geant4 simulation was performed and effect of the Cherenkov radiation on time resolution of the LYSO(Ce) crystal based counters was demonstrated. The first experiment to detect the
effect of Cherenkov radiation in the LYSO(Ce) crystal at BINP was carried out in June 2019. The time resolution depends on the angle of rotation of the crystal to beam line and could increased up to 20 ps. The time of signal arrival to the endcap of the LYSO crystal depends on the angle of rotation of the crystal to beam line and could be up to 120 ps.

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