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LYSO based precision timing calorimeters

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Abstract. In this report we outline the study of the development of calorimeter detectors using bright scintillating crystals. We discuss how timing information with a precision of a few tens of pico seconds and below can significantly improve the reconstruction of the physics events under challenging high pileup conditions to be faced at the High-Luminosity LHC or a future hadron collider. The particular challenge in measuring the time of arrival of a high energy photon lies in the stochastic component of the distance of initial conversion and the size of the electromagnetic shower. We present studies and measurements from test beams for calorimeter based timing measurements to explore the ultimate timing precision achievable for high energy photons of 10 GeV and above. We focus on techniques to measure the timing with a high precision in association with the energy of the photon. We present test-beam studies and results on the timing performance and characterization of the time resolution of LYSO-based calorimeters. We demonstrate time resolution of 30 ps is achievable for a particular design.

1. Introduction

High energy particle collider experiments are facing ever more challenging conditions, operating at todays accelerators, such as the Large Hadron Collider (LHC), capable of providing instantaneous luminosities of $10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and above. The high center of mass energy, the large number of simultaneous collisions of beam particles in the experiments and the very high repetition rates of the collision events pose huge challenges. Current upgrade plans for the LHC, the High Luminosity LHC (HL-LHC), future energy upgrades of the LHC or next generation hadron colliders such as the Future Circular Collider (FCC) will push the boundaries even further. These operational conditions result in extremely high particle fluxes, causing very high occupancies in the particle physics detectors operating at these machines. A precise timing information with a precision of around 10 ps and below is seen as a major aid in the reconstruction of the physics events under such challenging conditions.

The rate of simultaneous interactions per bunch crossing (pileup) at the HL-LHC is projected to reach an average of 140 to 200. The large amount of pileup increases the likelihood of confusion in the reconstruction of events of interest, due to the contamination from particles produced in different pileup interactions. The ability to discriminate between jets produced in the events of interest, especially those associated with the vector boson fusion processes, and jets produced by pileup interactions, will be degraded, the missing transverse energy resolution will deteriorate, and several other physics objects performance metrics will suffer.

One way to mitigate pileup confusion effects, complementary to precision tracking methods, is to perform a time of arrival measurement associated with a particular layer of the calorimeter, allowing for a time assignment for both charged particles and photons. Such a measurement with a precision of about 20 to 30 ps, when unambiguously associated to the corresponding energy measurement, will significantly reduce the inclusion of pileup particles in the reconstruction of the event of interest given that the spread in collision time of pileup interactions is about 200 ps. The association of the time measurement to the energy measurement is crucial, leading to a prototype design that calls for the time and energy measurements to be performed in the same active detector element. We have demonstrated in the past that full absorption crystal calorimeters as well as crystal sampling calorimeters can achieve such a precise timing measurement [1, 2].

2. Experimental Setup

Our previous results on precision timing with LYSO based calorimeters [2] were obtained with multi-channel plate photo multiplier (MCP-PMT) as photo detectors. MCP-PMTs feature a signal rise time on the order of 100 ps. For laser pulses with a FWHM of 50 ps we achieved a differential timing resolution of 7 ps [3], corresponding to a single device timing resolution of 5 ps. This performance is limited by the DRS based digitizer we use as a DAQ system, operating at 5 GS/s. In the studies described in this paper we use silicone multi pixel photon counters (SiPM). While they feature a slower rise time they allow a very good timing performance for large, coherent signals [4]. For our setup we use four different types of SiPMs with 10, 15 and 25 μm pixel size and 1×1 mm and 3×3 mm sensor size [5]. They are all read out with a DRS based digitizer through a clipping circuit as described in [4]. We do not amplify the output signal of the SiPMs, only exploiting the very large light yield of the LYSO scintillator and the intrinsic amplification of the SiPMs. Using the same fast laser pulses and DAQ system we obtain a differential timing resolution between two SiPMs of better than 10 ps, very similar to the MCP-PMT performance.

The experimental setup we use for the calorimetric timing measurements consists of a single cell of a sampling calorimeter with 29 layers of LYSO crystal and tungsten absorber. The lateral dimensions are $14 \times 14\,\mathrm{mm}^2$. The total depth of the cell is about 11.5 cm with the LYSO plates having a thickness of 1.5 mm. The scintillation light from the LYSO plates is extracted with four wave length shifting (WLS) fibers. The same cell has been used to measure the timing performance in comparison to the timing performance of a single cube of LYSO [2]. More details of the calorimetric performance of the Shashlik configuration are discussed in references [6] and [7].

In addition to plastic WLS fibers we also tested quartz capillaries filled with liquid wave length shifter using DSB as a wave length shifting agent [8]. To optically couple the quartz capillaries to the SiPMs we use a clear plastic fiber light guide which is connected to the end of the quartz capillary with a metal sleave tube. The same clear fiber coupler is used for the plastic WLS fibers to maintain equivalent light collection efficiency. The ratio of the light collection efficiency between the plastic fibers and the quartz capillaries approximately scales with the ratio of the diameter of the plastic fiber and the liquid core of the quartz capillary. This ratio is about 3 for the fibers and capillaries we used.

As a timing reference we use a Photek 240 MCP-PMT. It is placed behind the calorimeter cell and detects secondary shower particles escaping from the Shashlik calorimeter cell as we did in our previous studies [2]. To extract the time of flight we measure the time difference between the reference counter and the calorimeter cell. The time stamp is extracted from a Gaussian fit to the peak of the reference counter pulse which resembles a Gaussian shape. For the time stamp from the calorimeter cell we perform a straight line fit to the rising edge of the pulse and extract the time at half of the maximal signal amplitude.

We measure the timing performance of the calorimeter cell with high energy electrons in a range between 20 GeV and 200 GeV in the CERN North Area test beam. The impact point of the electrons onto the calorimeter cell is measured with a fiber hodoscope with a precision of better than 1 mm. The timing results are extracted from events impacting in the center of the calorimeter cell in an area of 2x2 mm. As we are using a single calorimeter cell the containment outside this region is limited which affects the timing measurement.

3. Experimental Results

The timing precision extracted from a pulse improves as the rise time of the pulse gets shorter and as the signal over background improves. The rise time of the pulses from the shashlik calorimeter cell are driven by the time constants of the wave length shifter as we demonstrated previously [2]. The rise time of the LYSO scintillation signal and the rise time of the previously used MCP-PMT is much faster than the WLS time constants. As SiPMs feature a slower rise time than MCP-PMTs we studied the signal rise time with our new setup. In figure 1 we show the rise time of the pulses as a function of the signal amplitude. We observe that the the rise time

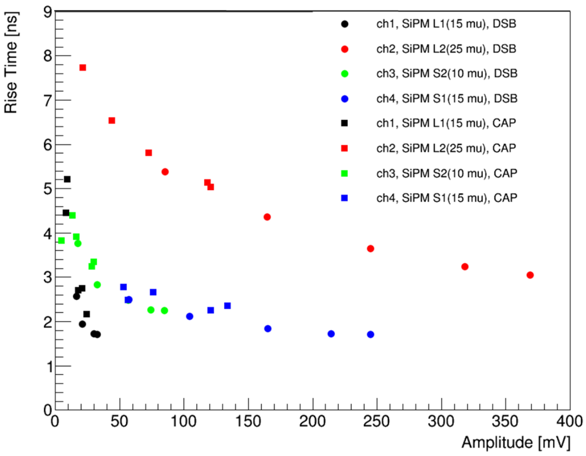

Figure 1. Rise time of the pulses as a function of the amplitude for the four different SiPMs. The data recorded with the plastic fibers and the quartz capillaries are distinguished as dots and squares. For each of the two data sets with plastic fibers and capillaries there are 5 measurements corresponding to beam energies of 20, 50, 100, 150 and 200 GeV.

of the pulses becomes shorter for larger pulses, reaching around 2 ns for the largest amplitudes in each channel. The amplitude dependency of the rise time is similar between different types of SiPMs but reaches is shortest value at different signal amplitudes. The bias voltage of the SiPMs is set to the same voltage, no individual optimization has been performed. The absolute signal amplitude in the SiPMs is different for the same beam energy which is expected as pixel count, sensor size and the light guide coupling efficiency varies. The clipping circuit used for all SiPMs is the same while the capacitance of the SiPMs is not. In figure 2 we show the time resolution of the four individual fibers as a function of their respective signal amplitude. Lines indicate the trend of the time resolution. We see a similar trend as for the rise times. However we also see that the improvement of the timing resolution is not just due to the faster rise times. The increased signal amplitude and the resulting improvement in the signal over background results in additional improvement.

For the same amplitude we find the same timing resolution with the capillaries and the plastic WLS fibers, both using DSB WLS agent. This further supports our previous findings that the the light propagation in the optical elements of a scintillation based calorimeter dos not significantly affect the performance at the level of 50 ps.

The light extraction efficiency of capillaries with liquid WLS remains sufficiently high for dose rates of 100 Mrad and beyond and for fluences of 10^{14}protons/cm^2 and beyond [7]. The energy

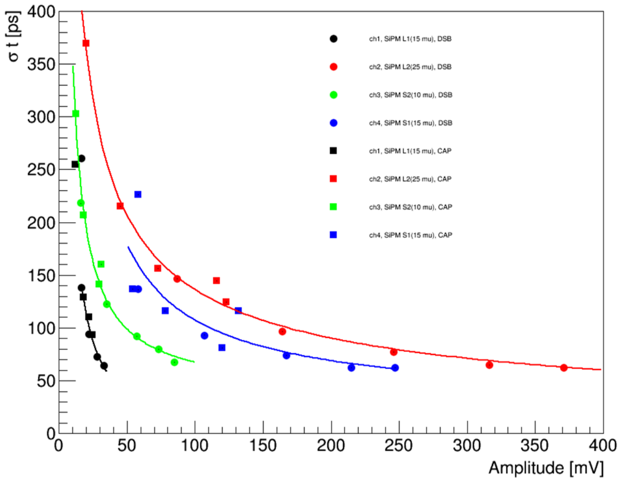

Figure 2. Time resolution achieved with the calorimeter cell using the signal of each of the SiPMs individually. The data for each SiPM consists of two sets, one with the DSB WLS plastic fiber and one with the capillaries with a liquid DSB based WLS. The time resolution improves with increasing signal amplitude. The best time resolution per fibre is around 60 ps for all of the channels. The amplitude at which this performance is achieved varies.

resolution performance of the LYSO/tungsten cell is not limited by photo statistics but the sampling fraction. The timing performance at lower energies could be improved by increasing the raw signal. This could be achieved by using larger diameter capillaries.

4. Summary

We present timing performance studies on a LYSO/tungsten Shashlik calorimeter cell with wave length shifting fiber and capillary readout with SiPMs as photo detectors and a DRS based fast digitizer data acquisition. We find a timing performance which reaches around 60 ps per individual readout fiber and better than 50 ps when combining the information from four fibers. Our results demonstrate that timing resolution of a few 10 ps can be achieved with scintillator based calorimeters even when complex optical readout schemes are employed. SiPMs are suitable as photo detectors for precision timing calorimeters.

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