Precision Timing Calorimeter for High Energy Physics

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Abstract

Scintillator based calorimeter technology is studied with the aim to achieve particle detection with a time resolution on the order of a few 10 ps for photons and electrons at energies of a few GeV and above. We present results from a prototype of a $1.4 \times 1.4 \times 11.4 \text{ cm}^3$ sampling calorimeter cell consisting of tungsten absorber plates and Cerium-doped Lutetium Yttrium Orthosilicate (LYSO) crystal scintillator plates. The LYSO plates are read out with wave lengths shifting fibers which are optically coupled to fast photo detectors on both ends of the fibers. The measurements with electrons were performed at the Fermilab Test Beam Facility (FTBF) and the CERN SPS H2 test beam. In addition to the baseline setup plastic scintillation counter and a MCP-PMT were used as trigger and as a reference for a time of flight measurement (TOF). We also present measurements with a fast laser to further characterize the response of the prototype and the photo sensors. All data were recorded using a DRS4 fast samplig digitizer. These measurements are part of an R&D program whose aim is to demonstrate the feasibility of building a large scale electromagnetic calorimeter with a time resolution on the order of 10 picoseconds, to be used in high energy physics experiments.

Keywords: Time of flight detector, Precision timing, LYSO, MCP, pico-second timing

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1. Introduction

Modern detector technologies, in particular the availability of fast and precise digitizing and sampling electronics, enable timing measurements with a precision of order ps. There is a broad range of developments ongoing introducing detectors with such precision into particle physics experiments. The ability to use 4-dimensional information greatly enhances the event reconstruction capability. A common application is the improvement of the signal to noise ratio of a given measurement by using the consistency of a time of arrival measurement of a multi particle final state or the consistency of a location in 4D space with a vertex location measured with a tracking device.

The high luminosity upgrade of the Large Hadron Collider (HL-LHC) at CERN [1] is expected to provide instantaneous luminosities of $5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$. The enhanced data rates will provide the datasets necessary to perform precision measurements of the Higgs couplings, probe rare Higgs processes, study the scattering of longitudinally polarized W bosons, and search for physics beyond the standard model.

The rate of simultaneous proton-proton interactions per bunch crossing (pileup) 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 interests, 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.

The detectors operated at the LHC have very high performance tracking devices. They allow to associate charged particles to primary interaction vertices with good precision, even in very dense environments such as HL-LHC. Photons however are mostly identified by the electromagnetic calorimeters. In particular jets consist on average of 30 % neutral mesons which to a large fraction get detected by their decay into photons. Some key physics signatures for the physics at HL-LHC contain high energy photons, most notably Higgs boson decays into photons. It is in this context that we study the possibility of measuring the time of arrival of particles with a calorimetric device, with an emphasis on timing measurement of photons in the energy

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range of a few GeV and up.

2. Precision timing technologies

Readout electronics capable of ps precision timing measurements are readily available. The challenge of building a full scale detector system for a particle physics detector lies in the primary sensing elements of the detector.

Micro channel plate detectors (MCP) have been shown to enable the detection of single ionizing particles with a precision of a few ps. They could be used as a single layer precision timing device or as an active element in a calorimeter. We have done studies demonstrating that the time structure of electromagnetic showers is sufficiently uniform so that a MCP as an active layer would allow the measurement of the time of arrival of electromagnetic particles with a precision of a few 10¹¹ ps [2]. Equipping a large particle physics detector in a high particle flux environment as the HL-LHC with a MCP based timing detector poses various challenges which are an area of active research [3].

Semiconductor based sensors are being explored for precision timing applications as well. On the single sensor level the timing precision for single charged particle detection is on the order of 100 ps [4]. It is being studied if the time of arrival of showers in calorimeters could be measured with significantly better precision utilizing the large number of synchronous particles in a shower and showers spreading over a large number of independent sensors.

For the studies presented in this document we focus on measurements of the time of flight using sampling calorimeters based on LYSO crystals. Due to its very high light yield ($\sim 30K$ photons/MeV) [5], and radiation tolerance [6], LYSO is the active element of one of the options considered for the upgrade of the Compact Muon Solenoid (CMS) detector at the HL-LHC [7].

In Figure 1 we present a simplified illustration of the major time scales associated to the timing measurement using a monolithic crystal calorimeter [8]. Upon entering the crystal, the photon or electron travels at the speed of light; these particles interact and beginning to shower, producing scintillation light. The time between the entry of the photon into the crystal and the first interaction is denoted by t_I and for high energy impinging particles it is the shower development time. The time period associated with the conversion of the incident photon to scintillation light is denoted by t_S . The scintillation light travels from the point of interaction to the photo detector at a velocity $c/\hat{n}$, where $\hat{n}$ is the effective index of refraction of the crystal. The time associated with the propagation of the scintillation light from the point of interaction to the photo detector is denoted by t_P . Once the scintillation light reaches the photo detector, the photons are converted into an electrical signal. The time period associated with this process is known as the photo detector signal transit time, t_T . Finally, the data acquisition (DAQ) system has a characteristic time constant t_D . Each of time periods described above will fluctuate or jitter on an event-by-event basis, contributing to the total time resolution.

Figure 1: Schematic cartoon of the most relevant contributions of a timing measurement with a monolithic, large scintillating crystal. The incident particle impinges on the crystal face from the left. Characteristic times of various contributions are defined in the colored boxes and defined in the text.

To characterize the time resolution of an inorganic crystal scintillator calorimeter we study the contributions due to fluctuations in the shower development, scintillation process, and light propagation to the photo detector. The very large number of scintillation photons in a LYSO crystal minimizes the fluctuations associated with the creation and transit of each particular scintillation photon for a LYSO-based detector providing a robust average. This in turn, allows the study of the effect of the light propagation time. For very high energy showers the number of scintillation photons is very large, even if crystals with lower light yield are used. The CMS ECAL, using lead tungstate crystals, features a time resolution for electrons of about 150 ps and a resolution of 70 ps among channels belonging to the same electromagnetic shower [9]. This also demonstrates the feasibility of calibrating a large scale detector in situ and maintain its performance in a challenging radiation environment.

3. Timing in LYSO Crystal-based Calorimeters

Besides the effects of the photo detector and DAQ electronics, timing performance in LYSO-based calorimeters is driven by three factors: shower profile fluctuations, scintillation light production, and optical transport. Stochastic processes during the development of an electromagnetic shower affect the time at which signals are observed, as both the transverse size and the depth of the shower can fluctuate event by event. Random processes in the scintillation mechanism and the randomization of the optical paths for the scintillation light affect both the speed of the signal formation and the time jitter. We study these effects using various independent experimental setups. In particular we present here studies of a LYSO-tungsten Shashlik calorimeter cell with a size of $1.4 \times 1.4 \times 11.4$ cm³, containing 29 layers of LYSO crystal plates with a thickness of 1.5 mm, interleaved with tungsten absorber plates. The scintillation light is read out with four wave length shifting fibers of about 1 mm diameter. The usage of the wavelength shifter enhances the efficiency of the light extraction from the LYSO tiles, but it introduces an additional time constant in the rise time [10]. In the configuration used here DSB is used as a wavelength shifter which has a time constants of 2 to 3 ns. A matrix of 4 by 4

such cells has been assembled and tested independently with electrons in the energy range between 4 GeV and 250 GeV in beam facilities in CERN and FNAL. The energy resolution of this prototype was measured to be $\frac{10\%}{\sqrt{E}} \oplus 1\%$ and the position resolution to be 0.6 mm for 100 GeV electrons. The radiation hardness of the LYSO crystals was tested up to 80 % of the fluence expected at HL-LHC assuming an integrated luminosity of 3 ab^{-1} . This qualifies the technology choice of a LYSO-tungsten Shashlik calorimeter as a viable option for a precision electromagnetic calorimeter. Using a single Shashlik calorimeter cell, read out with DSB1 fibers, Hamamatsu MCPs [12] and DRS4 [14] evaluation boards as DAQ system we have measured the time resolution for electron beams with energy varying between 4 GeV and 150 GeV. A Photek MCP [13] was used as a reference time measurement for the incoming electron.

Figure 2: The time resolution measured using the LYSO-tungsten shashlik calorimeter with light extracted using DSB1 wave length shifting fibers is plotted as a function of the effective signal amplitude from the MCP, and fitted to a $1/\sqrt{E}$ functional form.

The time resolution is plotted as a function of the beam energy in Figure 2. Here we show the result as a function of the effective signal amplitude from the MCP. The individual points correspond to energies of 4, 8, 16, 32 and 150 GeV. The containment for the single cell with the trigger counter used is about 80 % on average. We find that the dependence of the time resolution on beam energy follows a $1/\sqrt{E}$ functional form, reaching about 100 ps for a beam energy of 32 GeV and around 60 ps at 150 GeV. A fit of a $a/\sqrt{E} \oplus c$ suggest a constant term of the resolution of around 15 ps, in good agreement with estimated precision of the reference time measurement as discussed in one of our previous publications [10].

4. Timing Performance of the Hamatsu MCPs with DRS4 readout

Utilizing a laser [11] with a pulse width of less than 30 ps and a jitter of less than 5 ps we measured the performance of the Hamamatsu MCP sensors and the associated readout with the DRS4. We exposed two MCP sensors to the same laser pulses and measured the differential time resolution between the two sensors without any additional optical elements in the light path. As shown in Figure 3 we measure this differential

time resolution between the two sensors of 7.2 ps. From this we may infer a single channel resolution of around 5 ps.

Figure 3: Differential time resolution between two Hamamatsu MCPs, measured with a laser with a pulse width of better than 30 ps. We measure the resolution to be 7.2 ps which corresponds to a single channel resolution of around 5 ps.

In previous studies [10, 2] we have shown the contribution of the DRS4 readout to the time resolution to be around 5 ps. We conclude from this study that the performance of our light sensing chain for a large number of synchronous photons is indeed close to the limit of our DRS4 readout. The result of around 7 ps was achieved over a wide range of pulse intensities, covering the equivalent amplitude range of our studies with the LYSO assemblies. This result also confirms the assumption that our photo detector timing performance improves for large, synchronous pulses. Studies with a laser with significantly wider pulse width of a few ns did not yield the same good performance. This suggests that additional noise like phenomena may be induced in our setup by these very long light pulses. This is under further study and will be reported in a future communication.

5. Advanced Pulse Reconstruction

We have discussed previously that we do not see any evidence that the complexity of the light path in the crystal and light guiding elements has any impact on the observed pulse shape [10]. To study the impact of the observed dependency of the photo sensor and readout chain on the light pulse length we developed an advanced pulse reconstruction method. In this new method we extract the time of arrival of high energy electrons in our LYSO-tungsten Shashlik cell only from the very first part of rising edge of the measured pulse shape. Previously we used the part of the rising edge of the pulse shape in the range of 20 % to 60% of the maximum amplitude of the pulse. In Figure 4 we show a comparison of our previously published results [10] and the new pulse reconstruction utilizing only the very early leading edge of the pulse from the first rise above the noise level to 30 % of the maximum pulse amplitude.

We observe a significant improvement of the time resolution for high energy electrons measured with the LYSO-tungsten Shashlik cell. This suggests that the same noise like phenomena observed for long laser pulses may also affect the measurements

Figure 4: Comparison of the time resolution between a reference MCP and the LYSO-tungsten Shashlik cell for high energy electrons. Using only the very early part of the rising edge of the pulse we observe a significantly better timing performance compared to a time extraction using the entire rising edge.

using LYSO crystals. We recall that while LYSO has a very fast rise time its decay time constant is on the order of 40 ns. The effective rising edge of our LYSO-tungsten Shashlik cell is a convolution of the scintillation rise time, the light propagation time characteristics, the time characteristics of the wavelength shifter and the time characteristics of the photo sensor and the readout chain. For our LYSO-tungsten Shashlik cell we measure a rise time of 2.1 ns which is close to the time constant of the DSB wave length shifter used in the setup. This dominates the rise time and stretches it to a duration for which we started to observe noise like phenomena with laser pulses of equivalent length. We conclude from this that the performance of our setup is currently limited by these noise like phenomena. The leading edge fit extracts the time of arrival information in the LYSO-tungsten Shashlik cell from the early portion of the pulse which is less affected by this induced noise. Further studies are ongoing to quantify and possibly mitigate this effect. This is expected to yield a further improvement of performance.

6. Summary

In this study we present further characterization of the timing performance of LYSO-based calorimeters. We had previously shown results using a (1.7 cm)³ LYSO crystal that samples the electromagnetic showers created by electrons of various energies ranging from 4 GeV to 32 GeV at about 4.5 X₀, we inferred that the contribution to the time resolution from event-by-event fluctuations of the shower profile, the scintillation process, and the optical transit was less than 30 ps. We further study the effect of optical transit through WLS fibers and the light extraction efficiency in a LYSO-tungsten Shashlik calorimeter demonstrated that the use of a WLS fiber dominates the signal rise time of our setup which has a major impact on the time resolution. Studies with a fast laser suggest that our photo sensor and readout assembly has a differential time resolution of around 7 ps while this performance degrades for long light pulses. Studies of different pulse extraction methods

suggest that similar effects are present in our LYSO-tungsten setup. Restricting the time measurement to the very early part of the pulse yields a significant improvement of the timing performance. The best value achieved around 40 ps for a 32 GeV electron beam, compared to the previously achieved 100 ps.

In summary we demonstrated that a time resolution of a few 10 ps can be achieved with a LYSO based calorimeter with a design suitable for a high precision electromagnetic calorimeter to be operated at HL-LHC.

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