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Precision Timing Calorimeter for High Energy Physics

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***Abstract*—We present studies on the performance and characterization of the time resolution of LYSO-based calorimeters. Results for an LYSO sampling calorimeter and an LYSO-tungsten Shashlik calorimeter are presented. We demonstrate that a time resolution of 30 ps is achievable for the LYSO sampling calorimeter. We discuss timing calorimetry as a tool for mitigating the effects due to the large number of simultaneous interactions in the high luminosity environment foreseen for the Large Hadron Collider.**

I. Introduction

MODERN detector technologies, and the availability of fast and precise digitizing and sampling electronics, enable timing measurements with a precision of the order of picoseconds (ps). There is a broad range of ongoing developments introducing detectors with such precision into particle physics experiments. In particular, the acquisition of position, energy and time information enhances the capability for event reconstruction. A common application is the improvement of the signal to noise ratio of a given measurement by using the time of arrival measurement of a multi-particle final state, or the compatibility of the position and time in a detector 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 up to 5×10^{34} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$. 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. These additional interactions increase the likelihood of incorrectly reconstructing the main interaction due to contamination from the particles that they produce. The ability to discriminate between jets produced in the main interaction and those produced by pileup interactions will be degraded. In addition, the missing transverse energy resolution will deteriorate, and particle reconstruction will be degraded.

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One way to mitigate pileup effects in the calorimeters is to perform a simultaneous measurement of the energy and time of arrival. A time of arrival measurement, with a precision of about 20 to 30 ps, will significantly reduce the inclusion of pileup particles in the reconstruction of the main interaction – since the time spread of pileup interactions is about 200 ps. The association of the time of arrival and the energy measurement is crucial, and has led us to prototype designs that provide time and energy measurements from the same active detector element.

The detectors operated at the LHC have high performance tracking devices. These are used to associate charged particles to the primary interaction vertex. Good precision for finding the vertex is expected even in the very dense environment at the HL-LHC. Photons however are mostly identified by the electromagnetic calorimeters. Jets are comprised of $\sim 30\%$ neutral mesons. These mesons are mainly detected through their decays into photons. Some key signatures for the physics at HL-LHC contain high energy photons, most notably that of the Higgs boson through its decay to two photons.

It is in this context that we study the feasibility of measuring the time of arrival of particles with a calorimetric device. Particularly, we focus on timing measurements for photons in the energy range of a few GeV to 250 GeV.

II. Precision timing technologies

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

Micro channel plate (MCP) detectors enable the detection of single ionizing particles to a precision of a few ps [2]. They can be used as a single layer precision timing device or as an active element in a calorimeter. We have carried out studies demonstrating that MCPs, used as an active layer, can measure the time of arrival of electromagnetic particles with a precision of a few 10 ps [2]. Equipping a large particle physics detector in a high particle flux environment, such as the HL-LHC, with MCP based timing detectors poses various challenges which are an active area of research [3].

Semiconductor based sensors are also being explored for precision timing applications. At the single sensor level, the timing precision for single charged particle detection is on the

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order of 100 ps [4]. Significantly better precision is expected for electromagnetic showers in such calorimeters by utilizing the large number of hits from the charged particles traversing many independent sensors.

For the studies presented in this document we focus on measurements of the time of flight (time of arrival) 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].

Figure 1 shows the main contributions to the timing measurement using a monolithic crystal calorimeter [8]. Upon entering the crystal, the electron or photon (e/γ) travels at the speed of light; these particles interact and begin to shower, producing scintillation light. The time between the entry of the e/γ into the crystal and the first interaction is denoted by t_I, the start of the shower development. The time period associated with the conversion of the cascade particles to scintillation light is denoted by t_S. The scintillation light travels from the point of interaction to the photo detector at a speed $c/\hat{n}$, where $\hat{n}$ is the resultant index of refraction of the crystal. The time associated with the propagation of the scintillation light is denoted by t_P. Once the scintillation light reaches the photodetector, the photons are converted into an electrical signal. The time period associated with this process is known as the photodetector transit time, t_T. Finally, the data acquisition (DAQ) system has a characteristic time constant t_D. All time periods described above fluctuate on an event-by-event basis, thus contributing to the effective time resolution of the calorimeter.

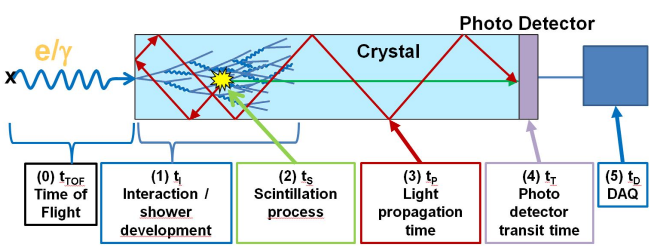

Fig. 1. A diagram of the main contributions to the timing measurement using a monolithic, large scintillating crystal. The incident particle impinges on the crystal face from the left. The characteristic times of the various contributions are defined in the colored boxes and defined in the text.

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. The large number of scintillation photons from an LYSO crystal significantly reduces the fluctuations for the mean time for the scintillation process, t_S. As a consequence, the effects of the light propagation time, t_P, can be studied in detail.

In summary, we note that even for low light yield crystal calorimeters, such as the CMS ECAL that uses lead tungstate crystals, a single channel time resolution of about 150 ps has been measured for electrons. A resultant time resolution of 70 ps has been achieved after including all the channels belonging to the electromagnetic shower [9]. This demonstrates the successful timing calibration and operation of a large scale detector in situ while maintaining performance in a challenging radiation environment.

III. Timing in LYSO Crystal-based Calorimeters

Shower profile fluctuations, scintillation light production, and optical transport affect the timing performance for LYSO-based calorimeters. 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 affect both the speed of the signal formation and its time jitter. We study these effects using two independent experimental setups.

First, a sampling calorimeter where a LYSO cube with linear dimensions of 1.7 cm (1.5 radiation lengths) is used as an active scintillation element. Its small size reduces optical transit jitter effects. The LYSO cube is placed immediately behind 4.5 radiation lengths of lead, and coupled to a MCP-PMT (see Figure 2). Using this LYSO-based sampling calorimeter, we measure the time resolution for electrons.

Second, we study a Shashlik calorimeter composed of alternating layers of tungsten and LYSO, in which the scintillation light is collected and transported using wavelength shifting (WLS) fibers. In this setup, the optical transit time fluctuations through the WLS is the dominant effect contributing to the effective time resolution of the calorimeter.

A. *Timing Studies of the LYSO-based Sampling Calorimeter*

The LYSO sampling calorimeter was used to study the combined effects of the shower profile fluctuations, the scintillation mechanism in LYSO, and the optical transit time. The LYSO crystal is wrapped in Tyvek and interfaced to a Hamamatsu R3809 MCP-PMT [10] using an optical coupler [11]. A Photek 240 MCP-PMT [12] is placed upstream of the calorimeter and is used to measure the reference time (t_0). A diagram and a photograph of the experimental setup are shown in Figure 2.

A plastic scintillator, approximately 2 mm by 2 mm in cross sectional area, placed upstream of the reference time detector, is used to trigger the DAQ readout on the DRS4 waveform digitizer [13]. Large (5 cm thick) lead bricks are placed upstream of the Hamamatsu R3809 MCP-PMT, out of the path of the beam. These shield the photodetector from stray particles produced in events where an electromagnetic shower occurs upstream of the lead radiator. Using the same experimental setup without the LYSO active element in place, we find that stray shower events yield less than 10% contamination and give a negligible effect on the scintillation signal.

The time of flight measurements are performed using the LYSO sampling calorimeter for electron beams with energies ranging from 4 GeV to 32 GeV. The resulting time of flight

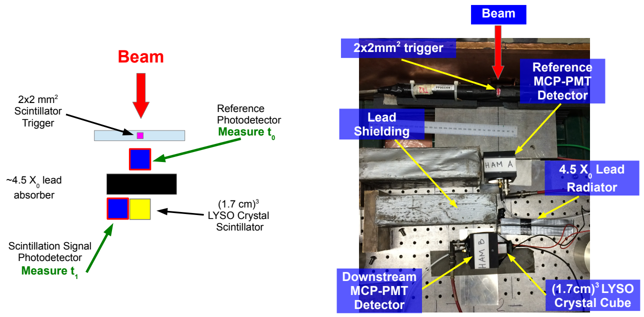

Fig. 2. A diagram of the experimental setup for the time of flight measurement using the LYSO sampling calorimeter is shown on the left, along with a photograph of the experimental setup shown on the right.

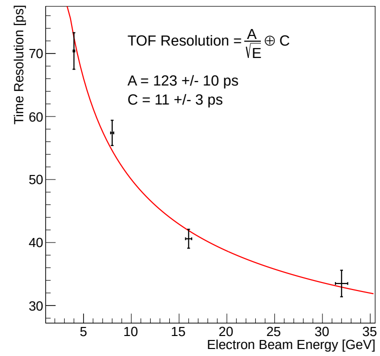

Fig. 4. The time resolution measured using the LYSO cube sampling calorimeter is plotted as a function of the electron beam energy, and fitted to the sum of a $1/\sqrt{E}$ term and a constant term. Note that the energy absorbed in the LYSO cube is only a small fraction of the total incident electron energy.

distributions are shown in Figure 3. A time resolution of 34 ps for a beam energy of 32 GeV is obtained.

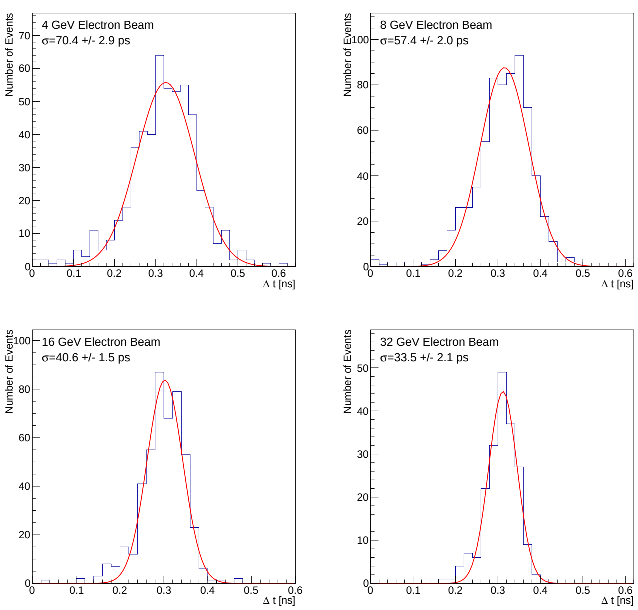

Fig. 3. Time of flight distributions for the LYSO cube sampling calorimeter for electron beams with energies of 4, 8, 16 and 32 GeV.

The time of flight resolution is plotted as a function of the beam energy in Figure 4. We fit the data to the sum of a $1/\sqrt{E}$ term and a constant term, finding a constant term of about 11 ps with a statistical uncertainty of about 30%.

We measure the contribution to the time resolution of the photodetector and the DAQ electronics to be about 20 ps. From the 34 ps measurement from the 32 GeV data, we infer that the combined contribution to the time resolution from the shower profile fluctuations, the scintillation mechanism, and the optical transit inside the LYSO cube is below ~ 27 ps. In future studies, we intend to separate these effects, in order to better isolate the impact of each of these components.

B. Timing Studies of the LYSO-Tungsten Shashlik Calorimeter

We study the time resolution of a LYSO-tungsten Shashlik calorimeter, one of the proposed choices for the Phase 2 upgrade of the CMS endcap calorimeter system [7]. In particular we present studies using a calorimeter cell of 1.4x1.4x11.4 cm^3, containing 29 layers of LYSO crystal plates with a thickness of 1.5 mm, interleaved with 2.5 mm thick tungsten absorber plates (see Figure 5). The cell corresponds to approximately 25 radiation lengths. The scintillation light is read out by four wavelength shifting fibers of about 1 mm diameter. A matrix of 16 such cells (4 by 4) has been assembled and tested independently with electrons in the energy range between 4 GeV and 250 GeV in beam facilities at CERN and FNAL. The energy resolution of that prototype was measured to be $\frac{10\%}{\sqrt{E(GeV)}} \oplus 1\%$ and its position resolution to be 0.6 mm for 100 GeV electrons. The radiation hardness of the LYSO crystals was tested up to 200 mrad of gamma-rays [14] and with 800 MeV protons up to a fluence 3×10^{14} particles/cm^2 and 24 GeV protons up to a fluence 6.9×10^{15} particles/cm^2 [15]. This corresponds to fluences in the range expected at HL-LHC assuming an integrated luminosity of 3 ab^{-1}, thus qualifying the LYSO-tungsten Shashlik calorimeter as a viable option for a precision electromagnetic calorimeter at the HL-LHC.

In this study, a single Shashlik calorimeter cell equipped with DSB1 WLS fibers, Hamamatsu R3809 MCP-PMTs and a DRS4 evaluation board as DAQ system is used to measure the time of flight resolution for electrons. A Photek 240 MCP-PMT is placed downstream of the calorimeter to measure the reference time (t_0) for the incoming electron beam. Figure 6 shows a diagram and a photograph of the experimental setup.

The time resolution is plotted as a function of the beam energy in Figure 7. The data correspond to energies of 4, 8, 16, 32 and 150 GeV. The energy containment for the single cell is about 80 % on average. A time resolution of 60 ps for a beam energy of 150 GeV is obtained. We fit the data to the sum of a $1/\sqrt{E}$ term and a constant term, finding a constant term of about 14 ps, in good agreement with our estimated precision of the reference time measurement as discussed in a previous publication [16].

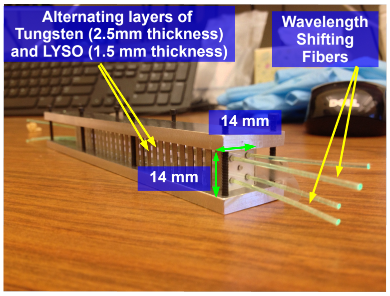

Fig. 5. The shashlik configuration based upon interleaved W and LYSO layers. Twenty-eight LYSO crystals and twenty-seven W plates comprise the module. Four WLS fibers are used to read out the scintillation light from the tiles.

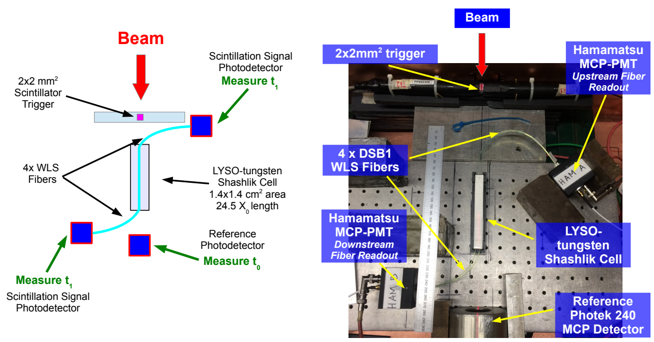

Fig. 6. A diagram of the experimental setup for the time of flight measurement using the LYSO-tungsten shashlik calorimeter with fiber signal extraction, along with a photograph of the experimental setup.

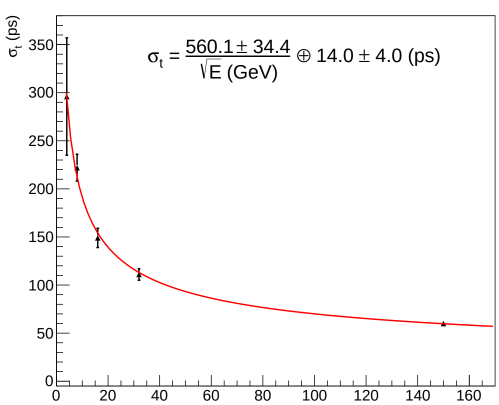

Fig. 7. The time resolution measured using the LYSO-tungsten shashlik calorimeter with light extracted using DSB1 wave length shifting fibers is plotted as a function of the electron beam energy, and fitted to a $1/\sqrt{E}$ functional form, with E in GeV.

IV. Timing Performance of the Hamamatsu MCPs with DRS4 Readout

Utilizing a laser [17] 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-PMT sensors and the associated readout with the DRS4 DAQ system. We exposed two MCP-PMTs 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 8 we measure this differential time resolution to be 7.2 ps.

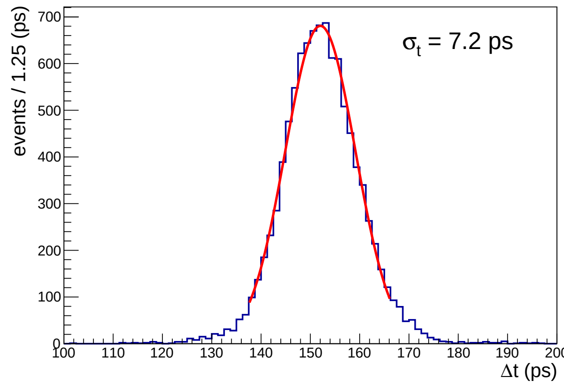

Fig. 8. Differential time resolution between two Hamamatsu MCPs, measured with a laser with a pulse width of better than 30 ps. We measure the differential resolution to be 7.2 ps.

In previous studies [2, 16] we have shown that the contribution from the DRS4 readout to the time resolution is around 5 ps. We conclude from this study that the performance of the MCP-PMTs, for a large number of synchronous photons corresponding to an output signal equivalent to that of the MCP-PMT response to 4 GeV electrons measured with the Shashlik cell, is indeed close to the limit of the 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 calorimeters in beam tests. This result also confirms the assumption that the photodetector timing performance improves for large, synchronous pulses. Studies using longer laser pulse widths, of a few ns, instead of 30 ps, degraded the time resolution, suggesting that additional noise like phenomena may be introduced by long light pulses. This hypothesis is under further study and will be reported in a future communication.

V. Summary

In this study we present a characterization of the timing performance of LYSO-based calorimeters. We show results using a 1.7 cm^3 (1.5 X_0) LYSO crystal that samples electromagnetic showers created in a 4.5 X_0 lead radiator by electrons with energies ranging from 4 GeV to 32 GeV. We infer that the contribution to the time resolution from shower profile fluctuations, the scintillation process, and the optical transit is less than 30 ps. We study the effect of optical transit through WLS fibers and the light extraction efficiency in a LYSO-tungsten Shashlik calorimeter. Studies with a fast laser suggest that our photo sensor and readout assembly has a differential time resolution of around 7 ps and that this performance degrades for long light pulses. In summary, we demonstrate that a time resolution of a few 10 ps can be achieved with a LYSO based calorimeter with a design suitable to be operated at HL-LHC.

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