Studies towards a Precision Timing Calorimeter for High Energy Physics Collider Experiments

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***Abstract*—Current and future high energy physics particle colliders are capable to provide instantaneous luminosities of $10^{34} cm^{-2} s^{-1}$ and above. The high center of mass energy, the large number of simultaneous collision of beam particles in the experiments and the very high repetition rates of the collision events pose huge challenges. They result in extremely high particle fluxes, causing very high occupancies in the particle physics detectors operating at these machines. To reconstruct the physics events, the detectors have to make as much information as possible available on the final state particles. We briefly discuss how timing information with a precision of around 10 ps and below can aid the reconstruction of the physics events under such challenging conditions. We discuss different detector concepts which can provide time measurements for charged particles and photons with a precision in the range of a few 10 ps. We present in detail updated measurements utilizing a Lutetium-yttrium oxyorthosilicate (LYSO) based calorimeter prototype. With an improved understanding of the signal creation, light propagation and detection characteristics we achieve a precision of down to 30 ps for electrons with energies of 30 GeV. Further we present beam test measurements with a multichannel plate based detectors and studies using silicon detectors. We discuss possible implementations based on these different technologies in a large scale particle physics detector.**

I. Introduction

THE high luminosity upgrade of the Large Hadron Collider (HL-LHC) at CERN [1] is expected to provide instantaneous luminosities of 5×10^{34} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and above. Future proton-proton colliders operating at much higher energies and collision rates are being discussed. 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 interactions per bunch crossing (pileup) is projected to reach an average of 140 to 200 at HL-LHC. 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 [2], [3], [4], [5].

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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, in particular for photons, leading to a prototype design that calls for the time and energy measurements to be performed in the same active detector element. It is in this context that we study the possibility of measuring the time of arrival of particles with a calorimetric device. The simultaneous measurement of the momentum and the time of arrival of a particle allows a 5-dimensional reconstruction of particles. This greatly enhances the full event reconstruction in particular in state of the art techniques such as particle flow reconstruction algorithms.

II. LYSO based calorimeter timing

While precision measurements of particle arrival times can be achieved with many different technologies we focus here on calorimetric technologies since this allows the timing of photons as well as charged particles. Among the wide range of calorimeter technologies we focus our studies on applications using scintillating crystals. Scintillating crystals can have very large scintillation light yields, providing a very large primary signal with a very fast rise time well below 1 ns. The CMS ECAL has achieved a timing performance of 100 ps and below for high energy electromagnetic particles [9], demonstrating the viability of calorimetric precision timing in a full scale detector. Our current R&D is based on LYSO crystals. They provide a much larger light yield compared to the PbWO used in the CMS ECAL. This allows for a greater flexibility in testing different detector geometries and light transport as well as simpler experimental setups.

We have presented previously studies of the timing performance of a LYSO-tungsten sampling Shashlik calorimeter and a $2 \times 2 \times 2\,cm^3$ solid LYSO crystal placed in the core of an electromagnetic shower [6]. We achieved a timing resolution of around 30 ps with the solid LYSO crystal cube for electrons of 32 GeV and 60 ps resolution with the Shashlik calorimeter at 150 GeV. With the same photo sensors and readout electronics we achieved a differential time resolution of around 7 ps using a short laser pulses with a width of 50 ps [7]. A detailed study of the effective light yield, the light propagation characteristics and the time response of the photo detectors suggests that the performance of the LYSO cube as well as the Shashlik cell is neither limited by shower fluctuations nor the photo statistics on the photo sensor. Rather do we observe a noise like feature in the MCP sensor pulses for the light from LYSO crystals which is not present in the response to the short laser pulses. We speculate that the noise like feature we observe in the MCP pulses is driven by the length of the LYSO scintillation light pulse which has a decay constant of more than 20 ns. As the time response of the MCP is in the range of 100 ps we suspect that intense light pulses which much longer time constants may cause such a feature. This is subject of further investigation and will be reported in a future communication. To further validate that neither photo statistics nor shower fluctuations contribute to the timing performance we carried out measurements using 4 Hamamatsu SiPMs to read out the four wave length shifting fibers of Shashlik cell as shown in Fig.1.

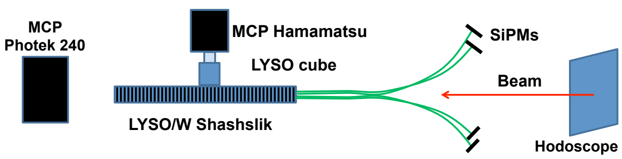

Fig. 1. Schematic of the experimental setup. The LYSO-tungsten Shashlik cell is read out with four wave length shifting fibers and four SiPMs. A Photek 240 MCP-PMT is used as reference detector. A fiber hodoscope provides a position measurement of the impact point of the beam particles onto the Shashlik cell transversely and horizontally.

We use two Hamamatsu SiPMs with a size of $1 \times 1\,mm^2$ and two SiPMs with a size of $3 \times 3\,mm^2$ and 10000 pixels each. The Shashlik cell is described in detail in [6]. The SiPM output signal is directly read by the DRS4 digitizer we use as a data aquisition system. No further amplification of the signal is performed. A minimal shaping of the SiPM pulses with a clipping circuit is done. In addition to the different photo detector the light extraction is modified in that we do not couple the wave length shifting fibers to the SiPM directly. Instead, they are coupled to a clear fiber which then transports the light to the SiPM. This setup allows to couple the SiPMs to an alternative wave lenght shifting light guide, in particular quartz tubes filled with liquid wave length shifter. This is a recent development which will provide much better radiation hardness than wave length shifter doped plastic fibers [10]. We will report on the timing performance of the wave length shifting capillaries in a future communication. In Fig.2 we show the results of the timing precision achieved with the two different photo sensors. The data acquisition as well as the reference timing is the same in both cases and described in [6]. We quote the precision of the reference timing measurement as 15 ps. As shown in Fig.2 the timing performance achieved with the SiPM readout is significantly better than the one with the MCP, despite the fact that the single photon timing resolution of the MCP is better than that of the SiPM. The laser measurements mentioned before demonstrate that we are able to improve this performance of the MCP for pulses with many photons, such as a short laser pulse, but not for longer pulses, such as a scintillation light pulse from a LYSO crystal. With the SiPMs on the other hand we are able to profit from the large number of photons generated by the LYSO and even exceed the performance of the MCP. We achieve a timing resoution of around 48 ps for electrons with an energy of 200 GeV and better 100 ps down to 20 GeV. This is to be compared to a resolution of around 100 GeV at 32 GeV with the MCP readout.

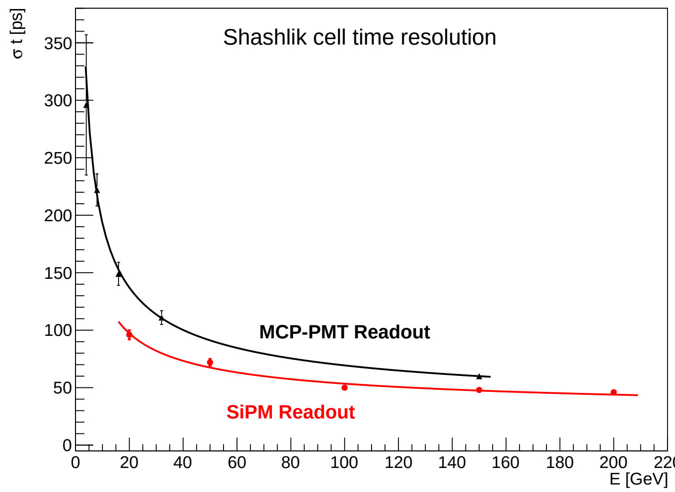

Fig. 2. Comparison of the timing performance of a LYSO-tungsten sampling calorimeter using two MCP-PMTs as photo sensors (black dots and line) with the readout using four SiPMs (red dots and line). We achieve a better performance with the SiPMs.

The lines in Fig.2 are from a fit to the data points with a square root dependency pulse a constant term. We note that the constant term for both fits is identical within errors and compatible with the reference time measurement. This suggests that indeed there are no indications of a fundamental limit on the precision achievable with a calorimetric timing measurements at the current level of precision we achieve.

III. Summary

We study a range of different detector technologies with respect to the ability to provide precision timing information for high energetic particles. We discuss possible implementations of these technologies in a large scale particle physics detector with a goal to enhance the ability of the detector to reconstruct particles in a very dense environment of modern high energy proton-proton colliders. In this studies 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 about 30 GeV at about 4.5 X_0 from which 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 studied the effect of optical transit through WLS and clear fibers in a LYSO-tungsten Shashlik calorimeter. We achieved a time resolution of around 60 ps for electrons of 150 GeV. The performance difference with respect to the solid LYSO crystal can entirely be attributed to the additional time constant of the wave length shifter use to extract the light efficiently from the Shashlik cell. Studies with a fast laser demonstrate that our photo sensor and readout assembly has a differential time resolution of around 7 ps, corresponding to a single channel resolution of 5 ps. In this document we present new studies with SiPM photo sensors reading wave length shifting fibers from a LYSO-tungsten Shashlik calorimeter cell. We achieve a better performance than with the MCP-PMT photo detectors, reaching 48 ps for 200 GeV electrons and better than 100 ps for 20 GeV electrons. We attribute the better performance of the SiPMs to a more stable output pulse response to large light pulses compared to the MCP-PMTs. These new measurements provide further evidence that the timing performance of our calorimeter prototypes is not limited by shower fluctuations nor by the available photo statistics at the photo detector level.

In summary we provide further demonstration 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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