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LYSO-based precision timing detectors with SiPM readout

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ABSTRACT

Particle detectors based on scintillation light are particularly well suited for precision timing applications with resolutions of a few 10's of ps. The large primary signal and the initial rise time of the scintillation light result in very favorable signal-to-noise conditions with fast signals. In this paper we describe timing studies using a LYSO-based sampling calorimeter with wavelength-shifting capillary light extraction and silicon photomultipliers as photosensors. We study the contributions of various steps of the signal generation to the total time resolution, and demonstrate its feasibility as a radiation-hard technology for calorimeters at high intensity hadron colliders.

1. Introduction

Precise time of arrival measurements have recently drawn much attention in the context of detector R&D for the high luminosity upgrade of the Large Hadron Collider (HL-LHC) as well as for future high energy hadron colliders. These hadron colliders must provide large instantaneous luminosity well above 10^{35} $cm^{-2}\,s^{-1}$. With accelerator and particle detector capabilities currently under design, such a high instantaneous luminosity will result in up to 200 simultaneous interactions (pileup) per bunch crossing. The ability to associate the origin of particles with different interaction points is crucial to the physics program, and precision timing would provide a new tool for achieving it, independently from track reconstruction.

Precision timing detectors can be used to discriminate between particles produced by different inelastic collisions [1]. For colliding particle beams with time spread of the order of 150–200 ps, as projected for the HL-LHC, a detector that can measure the time of arrival of particles can identify and reject particles from pileup collisions based on their time of arrival. Therefore with a timing detector with a timing precision of 20–30 ps, the number of pileup collisions which cannot be rejected based on their time of arrival will be about 20 to 40 and is similar to operational conditions in Run 2 of the LHC. A timing resolution in the range of 30–50 ps is also very interesting for optical time projection chambers which are discussed for large volume detectors in neutrino experiments and neutrino-less double-beta decay [2,3].

In our previous work in Ref. [4], we demonstrated the feasibility of achieving 30 ps resolution for electromagnetic showers using a sampling calorimeter based on LYSO crystal scintillators. Using micro-channel plate photomultipliers (MCP-PMTs) to read out photons on the edge of each LYSO layer, we achieved a time resolution of 55 ps for electrons with 32 GeV of energy. Using wavelength-shifting fibers to extract the light into the MCP-PMTs, we achieved a time resolution close to 100 ps. We concluded that the goal of 30 ps time resolution was within reach provided that we can realize similar performance using more economical photodetectors, extract the light using means that are radiation-hard, and achieve improved light collection efficiency. In this paper, we report on updated studies that demonstrate the time resolution performance using silicon photomultiplier (SiPM) detectors that are more economically scalable to the size of modern collider experiments, and radiation-hard wavelength-shifting quartz capillaries that can maintain its transparency under the harsh radiation conditions of the HL-LHC.

The paper is organized as follows. In Section 2 we give a brief overview of the SiPM sensors in the context of our research. In Section 3 we describe the experimental techniques we employ in our precision timing measurements as well as the specific setups we used for the studies presented in this paper. In Section 4.1 we present the results of timing measurements using SiPMs as photodetectors to read out scintillation light from LYSO crystals exposed to electrons in the GeV energy range. In Section 4.2 we evaluate the impact of the intrinsic timing performance of SiPM devices on the calorimeter time measurement by measuring the time resolution for SiPMs injected with light from a fast laser.

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2. SiPM

SiPMs are pixelated photodetectors that are increasingly used in contemporary high-energy physics experiments. Their compactness and form factor make them ideal for many applications including calorimeters [5] and charged particle detectors. They are also widely used for positron emission tomography (PET) detectors together with LYSO scintillating crystals for medical imaging purposes [6], where new studies have improved the timing resolution below 100 ps [7] and can yield substantial improvements in spatial resolution and imaging capabilities. The size of each SiPM device typically ranges between 1×1 mm^2 and 6×6 mm^2, with the size of each pixel ranging between 10 μm and 50 μm. SiPMs operate at relatively high gain between 10^5 and 10^6, and have single photon detection efficiency ranging from 10% to 50%.

SiPMs have a typical thermal dark count rate of about 0.1 MHz/mm^2 at room temperature, which can be strongly decreased when operated at lower temperatures. Typical operational temperatures range from 20 °C to 30 °C, but can be as low as −30°C. SiPMs have been tested for the impact of radiation damage up to an equivalent neutron rate of $2{\times}10^{14}$ cm^2, and its performance have been shown to be robust when operated at temperatures below 5 °C [8,9]. However, when operated at the same temperature, the thermal dark count rate increases significantly with large irradiation. The SiPMs used for our studies are Hamamatsu MPPC S12571-010P and S12571-015P both of size 1×1 mm^2, and S12572-15C and S12572-25C both of size 3×3 mm^2. These SiPMs are chosen to allow us to study the impact of the size of the sensitive area and the size of individual pixels on the timing performance. Studies of the impact of SiPMs from alternative manufacturers are left for future work. Some relevant details of the SiPM parameters are summarized in Table 1 below.

3. Setup and experimental apparatus

We performed measurements of SiPM properties in the laboratory using signals from a class 3R PiLas laser which produces light at a wavelength of 407 nm. Beam measurements were performed at the H4 beam-line of the CERN North-Area test-beam facility, which provides secondary beams of energies ranging between 20 GeV and 400 GeV. Electrons can be provided from tertiary beams up to 250 GeV with acceptable efficiency. The beams are composed of a mixture of electrons and pions. The electron fraction in the beam is typically larger than 75% and close to 100% for beam energy above 100 GeV.

The data acquisition (DAQ) system uses a CAEN V1742 switched capacitor digitizer based on the DRS4 chip [10], whose electronic time resolution has been measured to be 4 ps. Data readout for the laser-based measurements are triggered by an external digital trigger signal, while at the H4 beamline readout is triggered by a signal in a photomultiplier tube coupled to a 3 cm × 3 cm plastic scintillator located about one meter upstream from our detectors. A micro-channel plate photo-multiplier (MCP-PMT) detector is used to provide a very precise reference time-stamp in order to measure the time resolution of the SiPM signals.

3.1. Setup for laser-based SiPM timing measurements

SiPMs are mounted on a printed circuit board (PCB) with the circuit shown in Fig. 1. The high-pass filter is used to decrease the rise time of signal pulses by removing low-frequency components of the signal pulse. As a consequence, the resulting signal pulse will be smaller in amplitude and will have a faster rise time. We observe that a high-pass filter that reduces the rise time from 10 ns to 2 ns will also reduce the signal amplitude from 100 mV to 15 mV. The SiPMs are mechanically attached to an optical breadboard enclosed within a box lined with copper foil for RF shielding. The laser is injected via a light guide fiber mounted on an optical holder. The laser beam is immediately split by a 50/50 beam splitter and half of the light is directed onto the MCP-PMT while the other half of the light is directed onto the SiPM under test. A photograph of the setup is shown in Fig. 2. The Photek-240 MCP-PMT is used as the reference time detector whose time resolution has been measured to be below 7 ps for beam particles [11]. To cover a large range of laser beam intensity, neutral density (ND) filters with ND number between 0.2 and 2.4 are placed between the beam splitter and the SiPM under test.

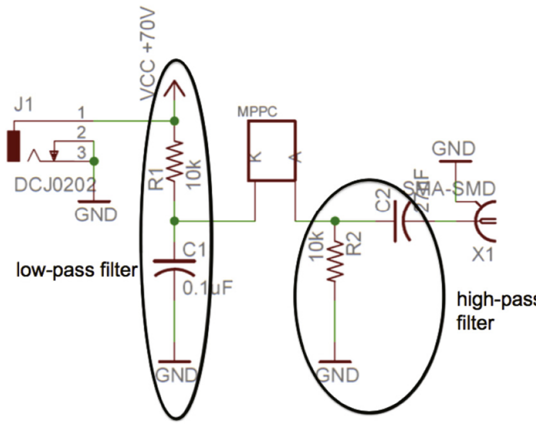

Fig. 1. A schematic diagram of the circuit used to read out the SiPMs. The SiPM is labeled as MPPC in the diagram.

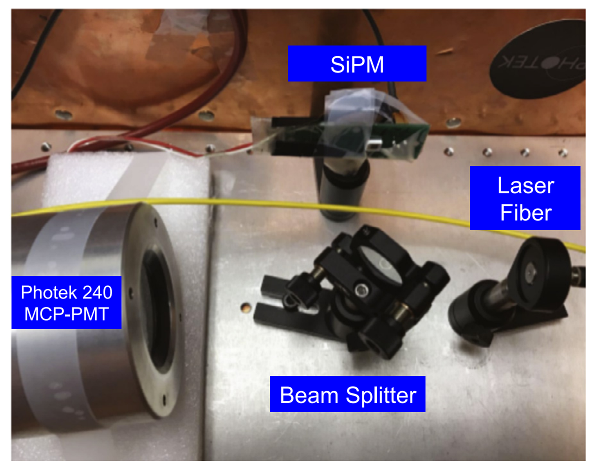

Fig. 2. Photograph of the Laser-based SiPM timing measurement setup.

3.2. Setup for timing measurements of scintillators with SiPM readout

The experimental setup we use for the calorimetric timing measurements is shown diagrammatically in Fig. 3 and consists of a single cell of a sampling calorimeter with 29 alternating layers of LYSO crystal and tungsten absorber, known as a Shashlik sampling calorimeter configuration. The lateral dimensions are 14×14 mm^2. The total depth of the cell is about 11.5 cm with the LYSO layers having a thickness of 1.5 mm. The same cell has been used to measure the timing performance in comparison to the timing performance of a single monolithic crystal of LYSO [4]. A scintillator counter of size 1×1 cm^2, mounted close to the calorimeter cell, is used to select events impinging on the center of the calorimeter cell. The scintillation light from the LYSO plates is extracted with four wavelength-shifting (WLS) fibers with 1 mm diameter. The fibers are coupled to four different types of Hamamatsu SiPMs with 10, 15 and 25 μm pixel size and 1×1 mm^2 and 3×3 mm^2 sensor size [12]. SiPMs are mounted on a printed circuit board (PCB) with the circuit shown in Fig. 1. The high-pass filter is used to decrease the rise time of signal pulses by removing low-frequency components