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Test beam studies of silicon timing for use in calorimetry

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ABSTRACT

The high luminosity upgrade of the Large Hadron Collider (HL-LHC) at CERN is expected to provide instantaneous luminosities of 5×10^{34} cm^{-2} s^{-1}. The high luminosities expected at the HL-LHC will be accompanied by a factor of 5–10 more pileup compared with LHC conditions in 2015, further increasing the challenge for particle identification and event reconstruction. Precision timing allows us to extend calorimetric measurements into such a high density environment by subtracting the energy deposits from pileup interactions. Calorimeters employing silicon as the active component have recently become a viable choice for the HL-LHC and future collider experiments which face very high radiation environments. In this paper, we present studies of basic calorimetric and precision timing measurements using a prototype composed of tungsten absorber and silicon sensor as the active medium. We show that for the bulk of electromagnetic showers induced by electrons in the range of 20–30 GeV, we can achieve time resolutions better than 25 ps per single pad sensor.

1. Introduction

Future colliders, including the high luminosity upgrade of the Large Hadron Collider (HL-LHC) at CERN, will operate with an order of magnitude higher instantaneous luminosity compared to what has been achieved at the LHC so far. With the increased instantaneous luminosity the rate of simultaneous interactions per bunch crossing (pileup) is projected to reach an average of 140–200. The large amount of pileup increases the likelihood of confusion in the reconstruction of particles from the hard scatter interaction with those 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 the 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 charged particles and photons. Such a measurement with a precision of about 20–30 ps, when unambiguously associated to the corresponding energy measurement, will reduce the effective amount of pileup by a factor of 10, given that the spread in collision time of the pileup interactions at HL-LHC is foreseen to be approximately 200 ps. The association of the time measurement with the energy measurement is crucial, and leads to a prototype design that calls for time and energy measurements to be performed in the same detector element. Since both the energy and time measurement are performed in the same detector element,[1] once an energy deposit is identified as originating from a pileup interaction, it can be unambiguously removed from event reconstruction.

Several alternative options to combine high resolution energy and timing measurements for calorimetry have been reported in Refs. [1–5]. In this paper, we describe the continuation of this program of study using a calorimeter prototype employing a 300 μm thick silicon pad sensor of 6×6 mm^2 size as the active element. Silicon-based calorimeters have recently become a viable choice for future colliders due to the radiation hardness of silicon, and the ability to construct highly granular detectors [6]. An

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[1] If there are no overlapping energy deposits in the same detector element from multiple particles.

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important example is the forward calorimeter proposed for the CMS Phase 2 Upgrade [7]. We study the timing properties of silicon-based calorimetry using a prototype composed of tungsten absorber and a silicon sensor produced by Hamamatsu [8]. A similar test was previously conducted at the CERN North Area, with a lead absorber followed by silicon sensors of 120–320 μm thickness [9].

The paper is organized as follows. General silicon timing properties and bench test results are described in Section 2. The test beam setup and experimental apparatus are presented in Section 3. The results of the test beam measurements are presented in Section 4. Sections 5 and 6 are devoted to discussion and conclusion, respectively.

2. General properties of silicon timing and bench test studies

For our measurements, we used a silicon sensor produced by Hamamatsu [8]. The thickness of the silicon was measured to be 325 μm. The transverse size of the sensor is 6×6 mm^2. The negative bias voltage was applied to the p-side of the silicon. The capacitance of the silicon diode is measured as a function of the bias voltage and shown in Fig. 1. We observe that the silicon is fully depleted above about 120 V. Timing measurements are expected to improve with larger bias voltage as the the carrier velocity increases.

The electric diagram of the silicon diode connections is presented in Fig. 2. Attention was paid to provide good filtering for bias voltage, to reduce ground loop effects, and to minimize inductive loop for the signal readout. The timing characteristics of the signal pulses are dominated primarily by properties of the silicon sensor rather than the details of the circuit.

The silicon diode was placed inside a light-tight box of thickness 1.5 cm, which also provides electromagnetic shielding. The box is made of 0.2 mm steel. The bias voltage was supplied to the circuitry by a cable with a balun filter, terminated with an SHV connector. The silicon diode output signal is read out through an SMA connector electrically grounded to the box. The dark current was measured at several values of the bias voltage. The maximum value of the dark current was less than 1.0 nA at −500 V, which is the largest bias voltage used in the measurements reported in this paper. The silicon box and bench test setup are presented in Fig. 2.

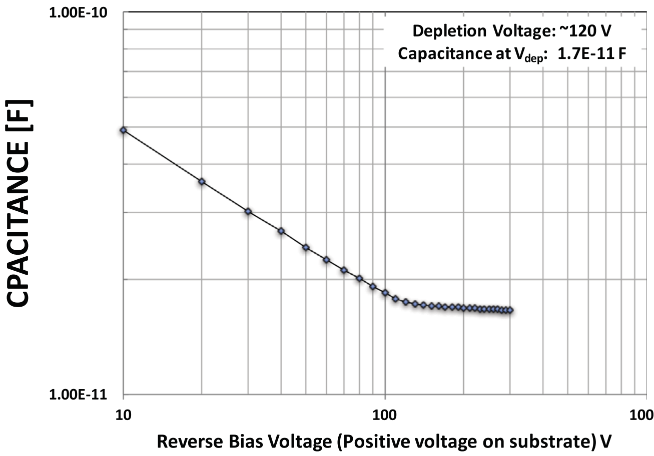

Fig. 1. The measured capacitance as a function of the applied bias voltage.

The signals from the silicon sensor were amplified by two fast, high-bandwidth pre-amplifiers connected in series. The first amplifier is an ORTEC VT120C pre-amplifier, and the second amplifier is a Hamamatsu C5594 amplifier. Using a pulse-generator, we measured the combined gain of the two amplifiers in series as a function of the input signal amplitude and found some degree of non-linearity for typical signals produced by the silicon sensor under study, and we corrected for them.

3. Test-beam setup and experimental apparatus

We performed the test-beam measurements at the Fermilab Test-beam Facility (FTBF) which provided a proton beam from the Fermilab Main Injector accelerator at 120 GeV, and secondary beams composed of electrons, pions, and muons of energies ranging from 4 GeV to 32 GeV. A simple schematic diagram of the experimental setup is shown in Fig. 3. A small plastic scintillator of transverse dimensions 1.8 mm ×2 mm is used as a trigger counter to initiate the read out of the data acquisition (DAQ) system and to select incident beam particles from a small geometric area, allowing us to center the beam particles on the silicon sensor. Next, we place a stack of tungsten absorbers of various thicknesses for measurements of the longitudinal profile of the electromagnetic shower. The silicon pad sensor is located within a metal box covered by copper foil, and is placed immediately downstream of the absorber plates. Finally, a Photek 240 micro-channel plate photomultiplier detector [1–4] is placed furthest downstream, and serves to provide a very precise reference timestamp. Its precision was previously measured to be less than 10 ps [3]. A photograph showing the various detector components is presented in Fig. 4. A differential Cherenkov counter is located further upstream of our experimental setup and provides additional particle identification capability. More details of the experimental setup are described in our previous studies using the same experimental facility in references [1–4].

The DAQ system is based on a CAEN V1742 digitizer board [10], which provides digitized waveforms sampled at 5 GS/s. The metal box containing the silicon sensor was located on a motorized *X*–*Y* moving stage allowing us to change the location of the sensor in the plane transverse to the beam at an accuracy better than 0.1 mm. A nominal bias voltage of 500 V was applied to deplete the silicon sensor in most of the studies shown below, unless noted otherwise.

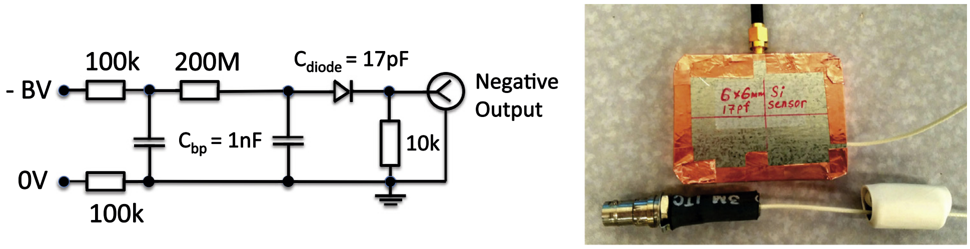

Fig. 2. The electric diagram for the silicon diode connections (left). External view of the box with silicon diode, and the bias voltage connection is shown below it (right).