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Precision Timing with Silicon Sensors for Use in Calorimetry

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Precision Timing with Silicon Sensors 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 $5 \times 10^{34} cm^{-2} s^{-1}$. The high luminosities expected at the HL-LHC will be accompanied by a factor of 5 to 10 more pileup compared with LHC conditions in 2015, causing general confusion for particle identification and event reconstruction. Precision timing allows 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 popular choice for the HL-LHC and future collider experiments which face very high radiation environments. 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 GeV to 30 GeV, we can achieve time resolutions better than 25 ps per single pad sensor.

1. Introduction

To meet the challenges posed by current and future high energy colliders, particle physics detectors have to operate in ever increasing particle fluxes and at higher interaction rates. Aside from finer segmentation both for tracking devices as well as for calorimeters, precision timing capabilities are being viewed as a very powerful additional functionality to enhance the physics performance of the detectors. Timing resolutions of order few 10 ps allow to cleanly associate signals to primary interactions. A 10 ps resolution is also equivalent to a spatial resolution of a few mm. This allows tracking of photons with such a precision which is hugely important in hadron collisions which have a significant fraction of the total energy carried by neutral mesons decaying into photons. Precision timing calorimetry with scintillating crystals [1] and multi-channel plates [2] is well established. In this paper we present our measurements using silicon sensors as sensitive element in a precision timing calorimeter. Large scale silicon sensors are considered as an upgrade option for the HL-LHC [3].

2. Experimental Setup

For our measurements, we used a silicon sensor produced by Hamamatsu [4]. The thickness of the silicon was measured to be 325 μm. The transverse size of the sensor is $6 \times 6\,\mathrm{mm}^2$. The negative bias voltage was applied to the p-side of the silicon. We observe that the silicon is

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fully depleted above about 120 V. Timing measurements are expected to improve with larger bias voltage as the the carrier velocity increases. 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 high voltage 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 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. Further details of the experimental setup can be found in [6]. As a reference timing sensor we use a Photek MCP-PMT 240. The data are recorded with a DRS [5] based ring sampler digitizer at at rate of 5 GS/s. Data was recorded at the FNAL M-test facility. Further details on the reference timing system and its performance can be found in [2]. The timing

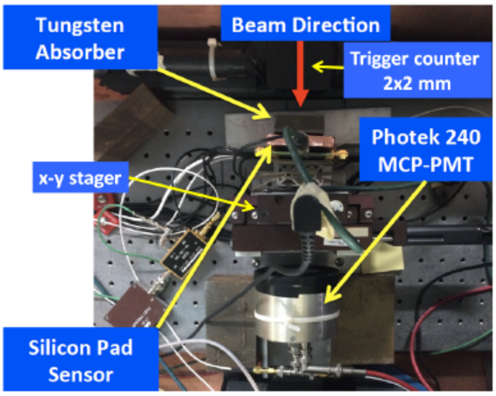

Figure 1. Experimental setup for the precision timing measurement of the Si pad sensor. The Si pad sensor is encapsulated in a metal box and placed as close as possible to the absorber. The beam impact point is defined with a size of $(2\text{mm})^2$. The beam is aligned transversely such that the response of the the Si pad sensor is maximized. The Photek reference counter is placed behind the Si pad sensor with absorber

information from the Si sensor is extracted from the sampled pulses by fitting a straight line to the rising edge of the pulse and determining the time at half the maximum amplitude. The timing information of the reference detector is extracted from a Gaussian fit to the peak of the pulses. A non-linearity from the amplifiers used is corrected in the data analysis. The quoted time resolutions are one sigma width of the differential timing between the reference sensor and the silicon pad sensor.

3. Experimental Results

Data were recorded at beam energies of 4, 8, 16 and 32 GeV with an electron beam, as well as with 120 GeV protons for calibration and alignment purposes. Showers are induced with a tungsten absorber of varying thickness to study the impact on the timing measurement. We have demonstrated in [2] that the temporal evolution of showers is very coherent. This is of crucial importance to exploit calorimeters as precision timing detectors. In Fig.: 2 we show the response of the Si pad sensor for the four beam energies we used. The measurement was performed after 6 radiation lengths of tungsten, approximately at the shower max. The mean value of the response is well correlated with the beam energy, demonstrating that even a single sensor features a calorimeter like response despite sampling only a very small part of the shower.

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The spread of the distributions in Fig.: 2 illustrates the RMS spread of the response. Due to

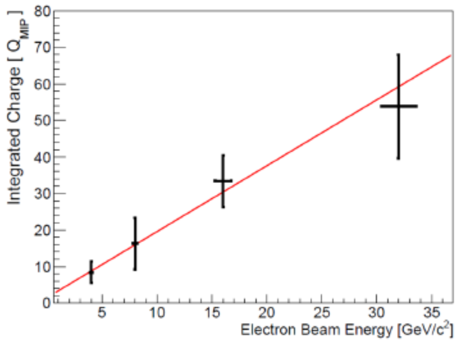

Figure 2. Mean signal amplitude and spread of the signal amplitude as measured with the Si pad sensor. The measurement was done for electron beams of 4, 8, 16 and 32 GeV. We find a good correlation between the beam energy and the mean signal amplitude. This demonstrates that despite the very limited containment of the Si sensor we have a clear pattern of a calorimetric measurement.

the limited containment of the single sensor the spread is considerable.

In Fig.: 3 we show the time resolution of the Si pad sensor measured beam energies of 4, 8, 16 and 32 GeV. The measurement was performed with an absorber thickness of 6 radiation lengths, approximately at shower max. The timing resolution improves with increased signal amplitude and reaches about 22 ps for beam energies of 32 GeV. The contribution of the reference timing sensor is not unfolded from this. It was determined to be less than 10 ps for an equivalent setup [2]. As we have shown in [2] one can improve the timing precision for electromagnetic showers

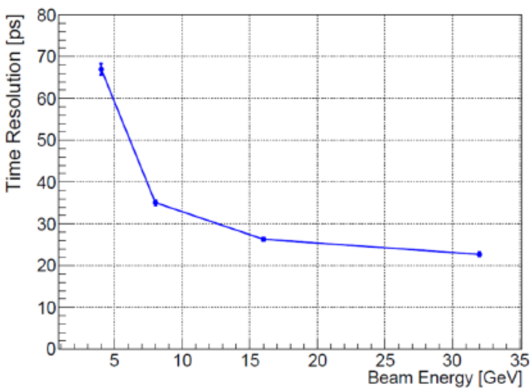

Figure 3. Time resolution of the Si pad sensor as a function of the incident beam energy. As shown in Fig.: 2 the signal amplitude measured in the Si pad sensor correlates well with the beam energy. We see an improved timing resolution as a function of the signal amplitude, reaching about 22 ps for an electron beam with an energy of 32 GeV

by performing multiple measurements on a single shower. Si pads such as the one we use can easily be arranged dense enough to perform 10 or more such measurements on a single shower. This is expected to further improve the performance. Such studies are being carried out and will be reported in the future. In Fig.: 4 we show the same data as used in Fig.: 3. However here the data is more finely binned in signal amplitude. The data from the four different beam energies is shown in different colors. We find that events with the same signal amplitude but different beam energy show the same time resolution. As we see from Fig.: 2 the signal amplitude in the Si pad fluctuates widely. Due to the small size of the pad the local shower fluctuations are substantial. This demonstrates that the time resolution is dominated by the signal amplitude in the sensor. Local shower fluctuations do not impact the timing measurement. This is further evidence to the very coherent temporal evolution of electromagnetic showers as we discussed in [1, 2]

4. Summary

We have measured the timing precision of a single silicon pad sensor in an electromagnetic shower. We find that the timing precision improves with the signal amplitude, reaching 22 ps on average measured with 32 GeV electrons after 6 radiation lengths of tungsten absorber. For events in the tail of the signal amplitude distribution we measure down to 16 ps. This suggests

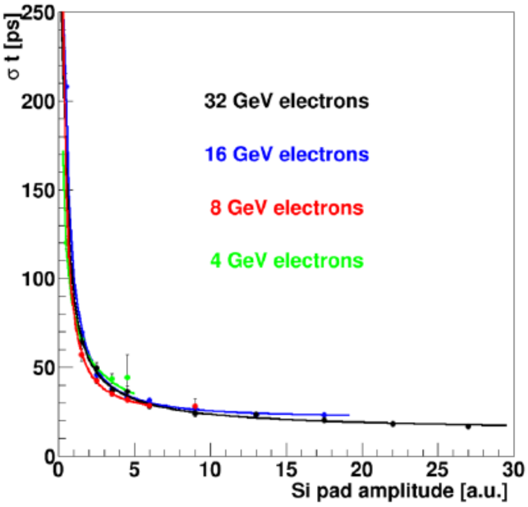

Figure 4. Time resolution as a function of the amplitude in the Si pad sensor. The data from the four different beam energies are separated by different colors. Due to the large spread of the signal amplitude the data from different beam energies overlaps. We find that the timing resolution scales only with the signal amplitude. Local shower fluctuations do not affect the timing measurements at the precision of our measurement.

that for higher energies the timing precision would improve further. We conclude that a silicon sampling calorimeter would allow to provide very precise timing information for electromagnetic showers.

4.1. Acknowledgments
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