

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 $5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. 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. In this article, 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.

Keywords:

1. Introduction

Future colliders, including the high luminosity upgrade of the Large Hadron Collider (HL-LHC) at CERN, will require improvements to the instantaneous luminosity by an order of magnitude or more 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 to 200. 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 object 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 the 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, 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 article, we describe the continuation of this program of study using a calorimeter prototype employing a silicon pad sensor of $6 \times 6 \text{ mm}^2$ size as the active element. Silicon-based calorimeters have recently become a popular choice for future colliders due to the radiation hardness of silicon, and the ability to construct highly granular detectors. An important example is the forward calorimeter proposed for the CMS Phase 2 Upgrade [6]. We study the timing properties of silicon-based calorimetry using a prototype composed of tungsten absorber and a silicon sensor produced by Hamamatsu [7].

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 [7]. The thickness of the silicon was measured to be $325\text{ }\mu\text{m}$. The transverse size of the sensor is $6\times 6\text{ mm}^2$. 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 Figure 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 carrier velocity increases.

The electric diagram of the silicon diode connections is presented in Figure 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.

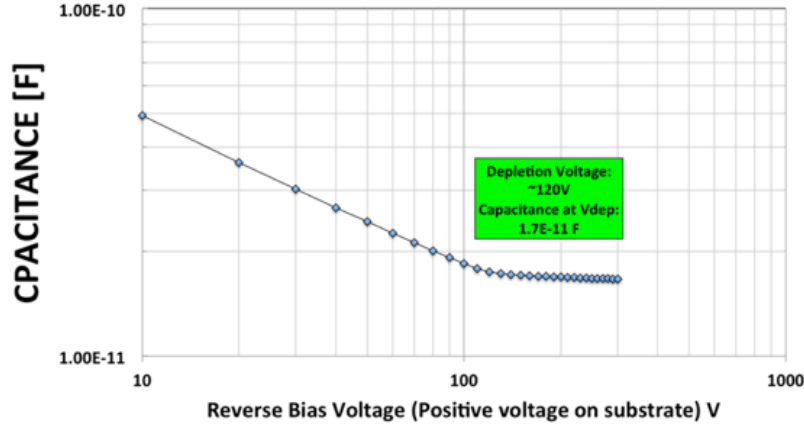


Figure 1: The measured capacitance as a function of the applied bias voltage.

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

89 is the largest bias voltage used in the measurements reported in this paper.
 90 The silicon box and bench test setup are presented in Figure 2.

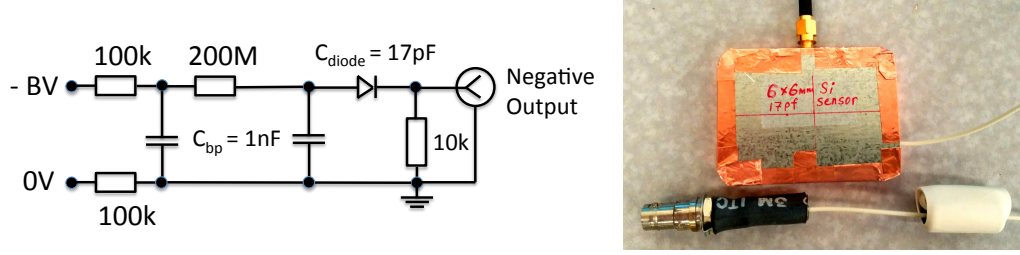


Figure 2: The electric diagram for the silicon diode connections (left). External view of the box with silicon diode, and the bias voltage connection is shown below it (right).

91 The signals from the silicon sensor were amplified by two fast, high-
 92 bandwidth pre-amplifiers connected in series. The first amplifier is an OR-
 93 TEC VT120C pre-amplifier, and the second amplifier is a Hamamatsu C5595
 94 amplifier. Using a pulse-generator, we measured the combined gain of the
 95 two amplifiers in series as a function of the input signal amplitude and found
 96 some degree of non-linearity for typical signals produced by the silicon sensor
 97 under study. The measured gain ranged from 200 for signals with amplitude
 98 around 0.15 mV to 650 for signals with amplitude around 10 mV.

99 3. Test-beam Setup and Experimental Apparatus

100 We performed the test-beam measurements at the Fermilab Test-beam
 101 Facility (FTBF) which provided a proton beam from the Fermilab Main In-
 102 jector accelerator at 120 GeV, and secondary beams composed of electrons,
 103 pions, and muons of energies ranging from 4 GeV to 32 GeV. A simple
 104 schematic diagram of the experimental setup is shown in Figure 3. A small
 105 plastic scintillator of transverse dimensions 1.8 mm×2 mm is used as a trig-
 106 ger counter to initiate the read out of the data acquisition (DAQ) system
 107 and to select incident beam particles from a small geometric area, allowing
 108 us to center the beam particles on the silicon sensor. Next, we place a stack
 109 of tungsten absorbers of various thicknesses for measurements of the longitu-
 110 dinal profile of the electromagnetic shower. The silicon pad sensor is located
 111 within a metal box covered by copper foil, and is placed immediately down-
 112 stream of the absorber plates. Finally, a Photek 240 micro-channel plate
 113 photomultiplier detector [1–4] is placed furthest downstream, and serves to

114 provide a very precise reference timestamp. Its precision was previously mea-
 115 sured to be less than 10 ps [3]. A photograph showing the various detector
 116 components is presented in Figure 4. A differential Cherenkov counter is
 117 located further upstream of our experimental setup and provides additional
 118 particle identification capability. More details of the experimental setup are
 119 described in our previous studies using the same experimental facility in ref-
 120 erences [1–4].

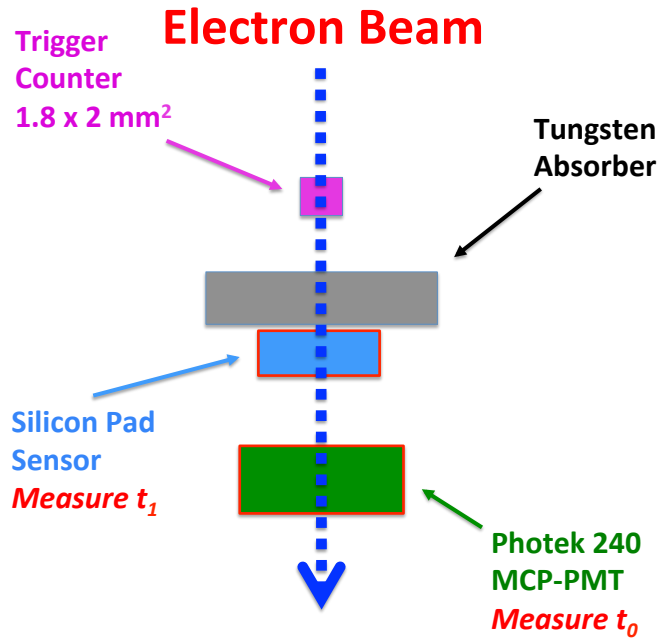


Figure 3: A schematic diagram of the test-beam setup is shown. The t_0 and t_1 are defined in Section 4.

121 The DAQ system is based on a CAEN V1742 digitizer board [8], which
 122 provides digitized waveforms sampled at 5 GS/s. The metal box containing
 123 the silicon sensor was located on a motorized X-Y moving stage allowing us
 124 to change the location of the sensor in the plane transverse to the beam at an
 125 accuracy better than 0.1 mm. A nominal bias voltage of 500 V was applied
 126 to deplete the silicon sensor in most of the studies shown below, unless noted
 127 otherwise.

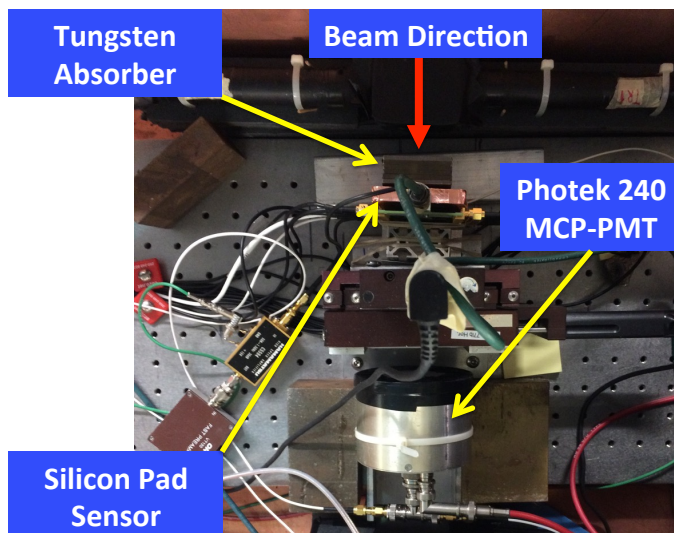


Figure 4: Test beam setup.

128 4. Test Beam Measurements and Results

129 Measurements were performed during December 2015, using the primary
 130 120 GeV proton beam, and secondary beams provided for the FTBF. Sec-
 131 ondary beams with energies ranging from 4 GeV/c² to 32 GeV/c² were used.
 132 Electron purity for those beams ranges between 70% at the lowest energy
 133 to about 10% at the highest energy. Stacks of tungsten plates with varying
 134 thicknesses were placed immediately upstream of the silicon device in order to
 135 measure the response along the longitudinal direction of the electromagnetic
 136 shower. The radiation length of tungsten is 3.5 mm, and the Moliere radius
 137 is 9.3 mm. The tungsten plate size is sufficient to fully contain the shower
 138 in the transverse dimension. Signals from the silicon sensor and the Photek
 139 MCP-PMT are read out and digitized by the CAEN V1742 digitizer, and
 140 example signal waveforms are shown in Fig. 5. The signal pulse in the silicon
 141 sensor has a rise time of about 1.5 ns, and a full pulse width of around 7 ns.
 142 This rise time is consistent with a time constant of a silicon sensor coupled
 143 to a 50 Ohm amplifier.

144 The CAEN digitizer is voltage and time calibrated using the procedure
 145 described in Ref. [9]. The total collected charge for each signal pulse is
 146 computed by integrating a 10 ns window around the peak of the pulse. The
 147 time for the reference Photek MCP-PMT detector is obtained by fitting the

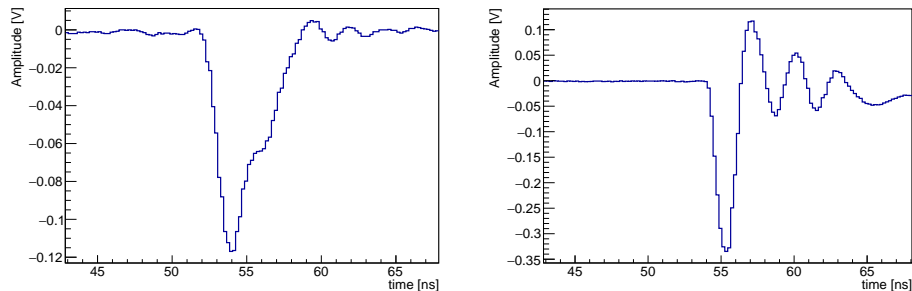


Figure 5: Examples of the signal pulse waveform for the silicon sensor (left) and the Photek MCP-PMT (right) digitized by CAEN V1742 digitizer board. The bias voltage applied to the silicon pad sensor is 500 V.

148 peak region of the pulse to a Gaussian function and the mean parameter
 149 of the Gaussian is assigned as the timestamp t_0 . The time for signals from
 150 the silicon sensor is obtained by performing a linear fit to the rising edge
 151 of the pulse and the time at which the pulse reaches 30% of the maximum
 152 amplitude is assigned as its timestamp t_1 . We measured the electronic time
 153 resolution of the CAEN V1742 digitizer as ~ 4 ps and neglected its impact
 154 on the timing measurements described below.

155 Electrons were identified using a combination of the gas Cherenkov counter
 156 provided by the FTBF and the signal amplitude in the Photek detector lo-
 157 cated further downstream of the silicon sensor. Electromagnetic showers
 158 induced by electrons produce significantly larger signals in the Photek MCP-
 159 PMT, while pions produce much smaller signals. After imposing the electron
 160 identification requirements the electron purity is between 80% and 90% for
 161 all beam conditions.

162 We begin by establishing the signal characteristics of a minimum-ionizing
 163 particle (MIP) using beams of 120 GeV protons and 8 GeV electrons with no
 164 absorbers upstream of the silicon pad sensor. To separate MIP signals from
 165 noise, we first collect data events with no beam and random trigger. The
 166 charge distribution for these noise runs is presented in Fig. 6. As expected,
 167 the charge distribution is centered at 0, and the RMS is about 2 fC.

168 In Figure 7, we show the response of the silicon sensor to the proton and
 169 electron beams without any absorbers upstream. We observe very similar
 170 response for these two cases, and measure an integrated charge of 4.5 fC and
 171 5.0 fC for the proton and electron beams, respectively. The measured charge
 172 is corrected for the gain of the amplifiers and attenuators used, and hence is

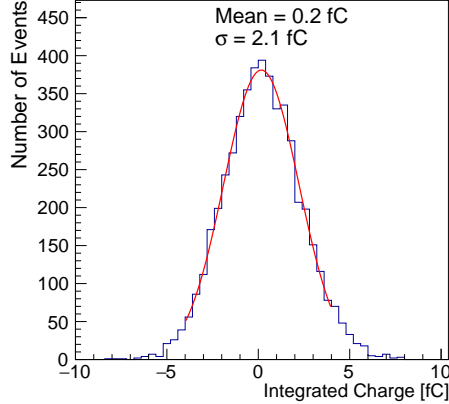


Figure 6: The distribution of charge integrated in the silicon sensor is shown for data events with no beam and random trigger.

the output of the silicon sensor. We expect that a MIP traversing a silicon sensor of thickness $325\ \mu\text{m}$ to produce roughly 35,000 electron-hole pairs, corresponding to a collected charge of about 5 fC. Thus, our measured value is in agreement with expectations. Having established the absolute scale of the response using MIPs, in our remaining studies we normalize all charge measurements to the charge integrated in the silicon sensor for one MIP, Q_{MIP} .

We study the response of the silicon sensor to electron beams of various energies after 6 radiation lengths (X_0) of tungsten absorber. The silicon sensor is expected to be sensitive to the number of secondary electrons produced within the electromagnetic shower, and therefore its response is expected to scale up with higher incident electron energy. In Figure 8, we show an example of the integrated charge distribution measured in the silicon sensor after 6 radiation lengths of tungsten, for runs with 32 GeV electrons. We plot the mean and RMS of these distributions as a function of incident electron beam energy in Figure 9. The uncertainties plotted show the RMS of the charge distribution. We observe a fairly linear dependence between the measured charge and the incident beam energy, for beam energies between 4 GeV and 32 GeV.

We also measure the time resolution between the silicon sensor and the Photek MCP-PMT, by measuring the standard deviation of the gaussian fit to the distribution of $\Delta t = t_0 - t_1$. We observe a systematic dependence of Δt

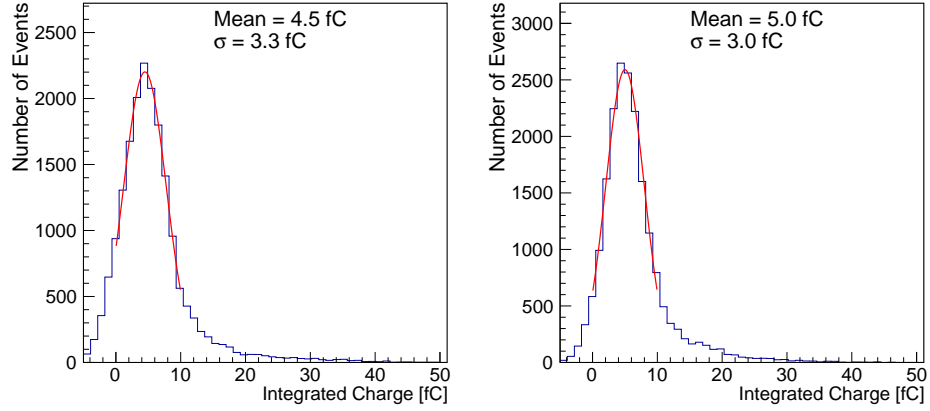


Figure 7: The distribution of charge integrated in the silicon sensor is shown for a beam of 120 GeV protons (left) and 8 GeV electrons (right) without any absorber upstream of the silicon sensor. These conditions mimic the response of the silicon sensor to a minimum-ionizing particle.

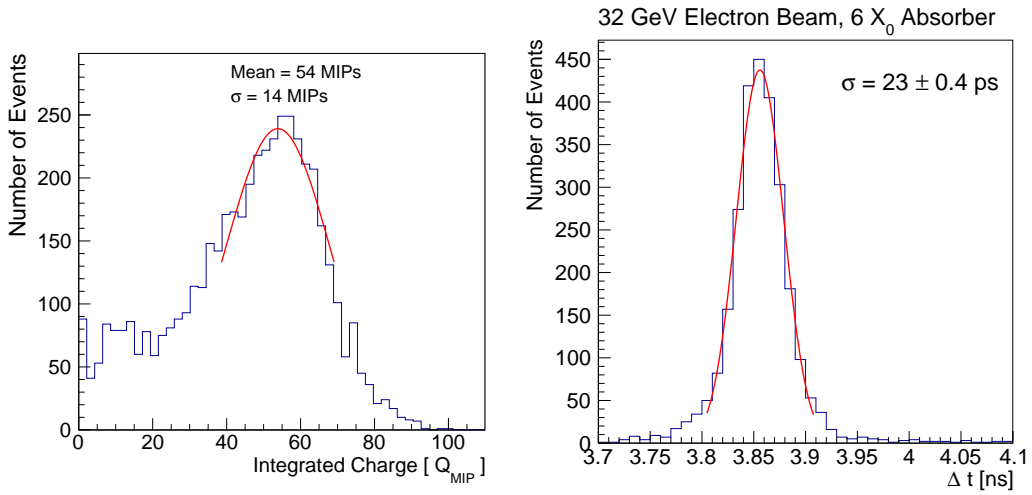


Figure 8: Left: An example of the distribution of integrated charge in the silicon sensor shown in units of charge measured for a MIP. Right: The distribution of Δt between the silicon sensor and the Photek MCP-PMT. A 32 GeV electron beam is used, and the silicon sensor is placed after $6 X_0$ of tungsten absorber.

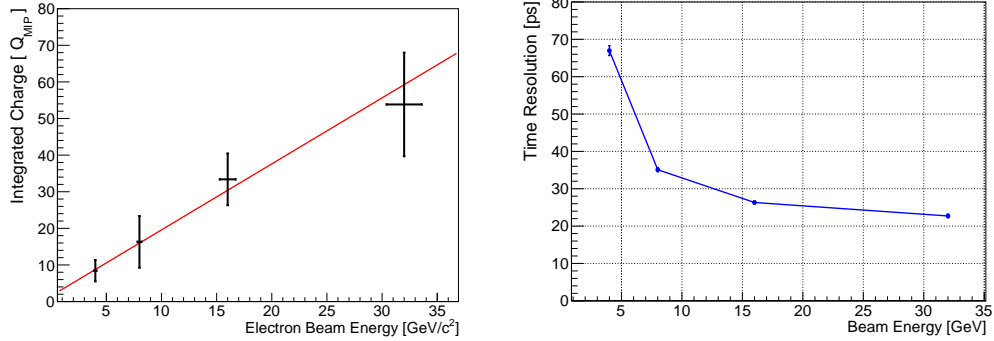


Figure 9: Left: The integrated charge in the silicon sensor expressed in units of the charge measured for a MIP is shown as a function of the electron beam energy. The uncertainty bands show the RMS of the measured charge distribution. The red line is the best fit to a linear function. Right: The measured time resolution between the silicon sensor and the Photek MCP-PMT reference is shown as a function of the electron beam energy.

on the total charge measured in the silicon detector, as shown in Figure 10. We perform a correction to Δt for each event using the measured charge in the silicon sensor. The correction is obtained from a second degree polynomial fit to the distribution of the Δt versus total charge collected in the silicon sensor, as shown in Figure 10. We verify that the correction flattens the dependence of the time measurement on the integrated charge, as shown on the right panel of Figure 10. An example of a corrected Δt distribution for 32 GeV electrons after $6 X_0$ is shown on the right of Figure 8. Other than the electron identification requirements, no additional selection requirements on the amplitude of the signal in the silicon sensor were made. The dependence of the measured time resolution on the beam energy is shown on the right of Figure 9. We observe an improvement in the time resolution as beam energy increases, and achieve a time resolution of 23 ps for the 32 GeV electron beam.

Furthermore, we study the response and time resolution of the silicon sensor along the longitudinal direction of the shower development. We measure the integrated charge and the time resolution as a function of the absorber thickness and present the results in Figure 11. A typical longitudinal shower profile is observed, consistent with previous studies performed using a secondary emission calorimeter prototype based on MCP's [3], as well as independent studies of silicon-based calorimeter prototypes [10]. The RMS of

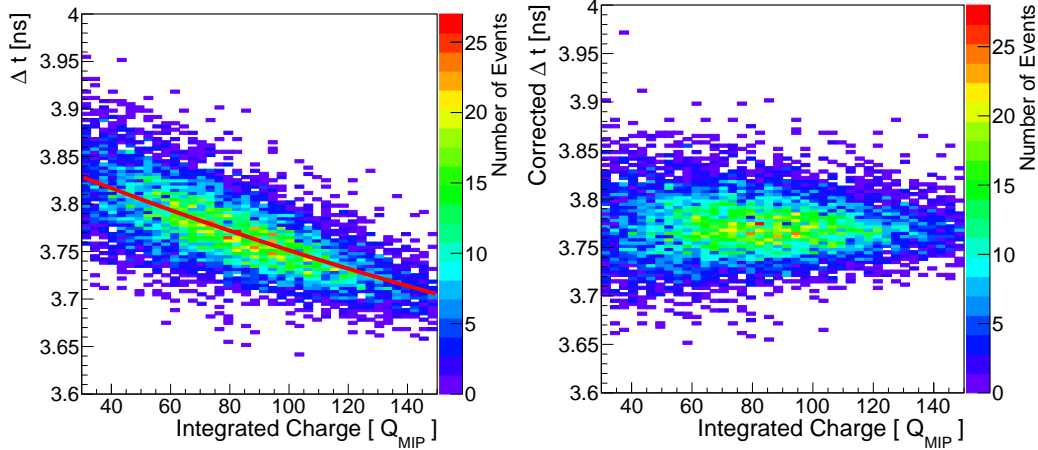


Figure 10: The dependence of Δt on the integrated charge in the silicon sensor is shown on the left. The red curve represents the fit to the profile plot of the two dimensional distribution, and is used to correct Δt for this effect. On the right, we show the corresponding two dimensional distribution after performing the correction.

the integrated charge at each absorber thickness is relatively large, due to a small size of the active element used in the experiment. We also observe that the time resolution improves as the shower develops towards its maximum in the longitudinal direction.

Finally, we studied the dependence of the time resolution as a function of the bias voltage applied to deplete the silicon sensor. The measurements are shown in Figure 12 for 16 GeV electrons after 6 X_0 of tungsten absorber. We find that the time resolution improves as the bias voltage is increased, which is expected on the basis of increased velocity of electrons and holes in silicon at larger bias voltage.

5. Discussion

From Figures 6 and 7, we observe that the noise of the prototype system is sufficiently low to extract signals from MIPs. Comparing the RMS of the noise distribution with the mean of the MIP signal, we find a signal-to-noise ratio around 2 to 2.5. A rough estimate from Figure 7 demonstrates that the efficiency to detect 120 GeV protons and 8 GeV electrons with no absorber present is larger than 80%. Based on the measurements for MIPs, we derive signal distributions for electromagnetic showers normalized to MIP response,

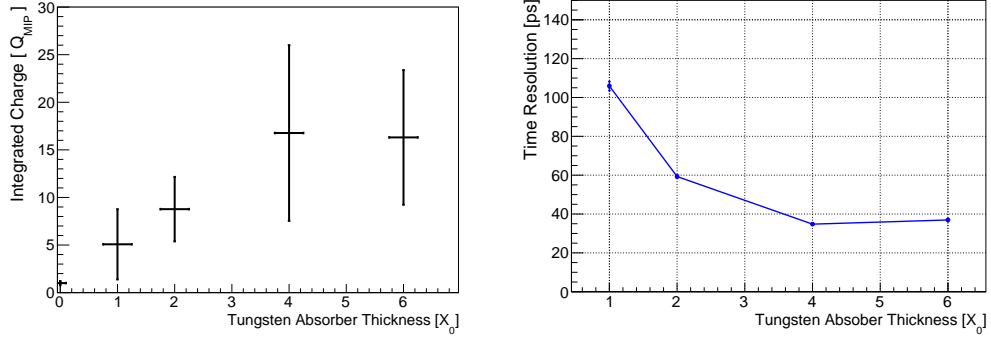


Figure 11: On the left, the integrated charge in the silicon sensor expressed in units of the charge measured for MIPs is shown as a function of the absorber (W) thickness measured in units of radiation lengths (X_0). The uncertainty bands show the RMS of the measured charge distribution. On the right, the time resolution between the silicon sensor and the Photek MCP-PMT reference is shown as a function of the absorber thickness.

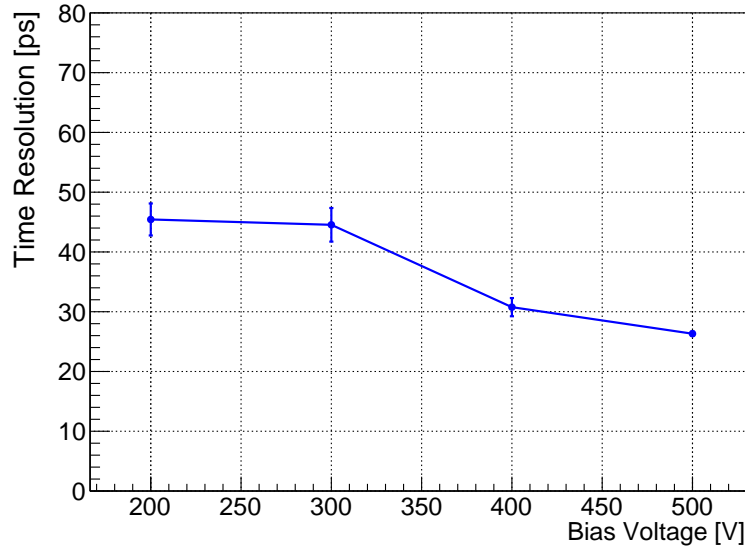


Figure 12: The time resolution between the silicon sensor and the Photek MCP-PMT reference is shown as a function of bias voltage applied on the silicon sensor.

234 and observe a relatively linear response to the electron beam energy in the
235 range from 4 GeV to 32 GeV after 6 X_0 of tungsten absorber, as shown in
236 Figure 9. We also measure a longitudinal shower profile in Figure 11 that is
237 consistent with similar past measurements.

238 Our results show that the time stamp associated with electromagnetic
239 showers induced by electrons with energy between 20 GeV and 30 GeV can
240 be measured with a precision better than 25 ps. Subtracting for the resolution
241 of the reference Photek MCP-PMT detector yields a precision close to 20 ps.
242 Moreover, we observe an improvement of the time resolution with the energy
243 of the electron, and more generally with an increase in the signal amplitude.
244 These measurements demonstrate that a calorimeter based on silicon sensors
245 as the active medium can achieve intrinsic time resolution at the 20 ps level,
246 as long as noise is kept under control. Time jitter arising from intrinsic
247 properties of the silicon sensor is demonstrated to be well below the 20 ps
248 level.

249 6. Conclusion

250 The best time resolution of 23 ps for a silicon sensor was achieved with
251 a 32 GeV beam and with the silicon sensor placed after 6 radiation lengths
252 of tungsten absorber. Based on our calibration data for the response of the
253 silicon sensor to MIPs, this measurement corresponds roughly to an average
254 of 54 secondary particles registered from the electromagnetic shower. We
255 observe a roughly linearly increasing response as the energy of the electron
256 beam is increased, and we observe a longitudinal shower profile consistent
257 with similar past measurements. This result yields further encouragement
258 to use silicon for active layers in calorimeters, as is planned for example for
259 the CMS Phase 2 upgrade [6], and explicitly demonstrates the opportunity
260 to use silicon for timing measurements in future calorimeters. To continue,
261 we plan to extend our studies to more realistic prototypes covering larger
262 transverse and longitudinal regions of the electromagnetic shower and using
263 multiple channels.

264 7. Acknowledgements

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