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Precision Timing In Silicon Based Calorimeters

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The high luminosity upgrade of the Large Hadron Collider (HL-LHC) at CERN is expected to provide instantaneous luminosities of $5 \times 10^{34}\mathrm{cm}^2\mathrm{s}^1$. The high luminosities expected at the HL-LHC will be accompanied by a factor of 5 to 10 more pileup compared with LHC conditions, 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.

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Future colliders, including the high luminosity upgrade of the Large Hadron Collider (HL-LHC) at CERN, will operate with an order of magnitude higher pileup compared to the LHC, causing detrimental impact on the accuracy of the event reconstruction. A novel way to mitigate the effects of pileup is to perform time measurements for particles arriving at a particular layer of the calorimeter, identify those particles produced from pileup interactions, and remove them from the reconstruction of the primary collision event. Silicon-based calorimeters have recently become a viable choice for future colliders, and the forward calorimeter proposed for the CMS Phase 2 Upgrade [1] is an important example. We present a study of the timing properties of silicon-based calorimeters using a prototype composed of tungsten absorber and a silicon sensor [2].

Measurements were performed at the Fermilab Testbeam Facility using proton and electron beams. Tungsten absorbers were placed in front of a copper enclosure holding the silicon sensor, and the time is measured with respect to a Photek-240 MCP-PMT, as shown in Figure 1. The charge distribution for noise events as well as typical signals for proton particles that behave similar to minimum ionizing particles (MIP's) and electron showers are shown in Figure 2. Large signals are observed for electromagnetic showers and are conducive to precision time measurements. The mean integrated charge is shown as a function of the absorber thickness and the beam energy in Figure 3.

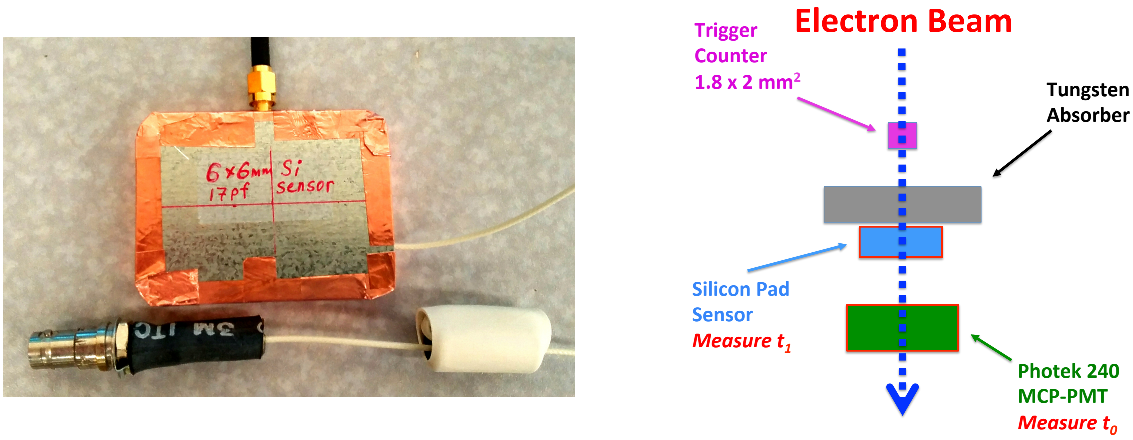

Figure 1: Left: Photograph of the metallic enclosure holding the silicon pad sensor. Right: A schematic diagram showing the component detectors and the experimental setup.

The signal pulses are digitized in time steps of 0.2 ns, and the time stamps are reconstructed using linear fits to the leading edge. The MCP-PMT reference time detector has a time resolution of about $7-8$ ps [3], while the digitizer has an electronic resolution of about $4-5$ ps. The time distribution for electromagnetic showers from 32 GeV electrons after 6 radiation lengths of absorber material is shown on the left of Figure 4. The time resolution is measured as the width parameter of a gaussian fit to the core of this distribution. An energy scan was performed, and the measured time resolution is shown as a function of the beam energy on the right of Figure 4. For the highest energy available, we obtained a time resolution of 23 ps. This measurement demonstrates that time resolution below 25 ps is achievable for electromagnetic showers using a silicon sensor based calorimeter.

We further investigate the time resolution as a function of the absorber thickness in Figure 5,

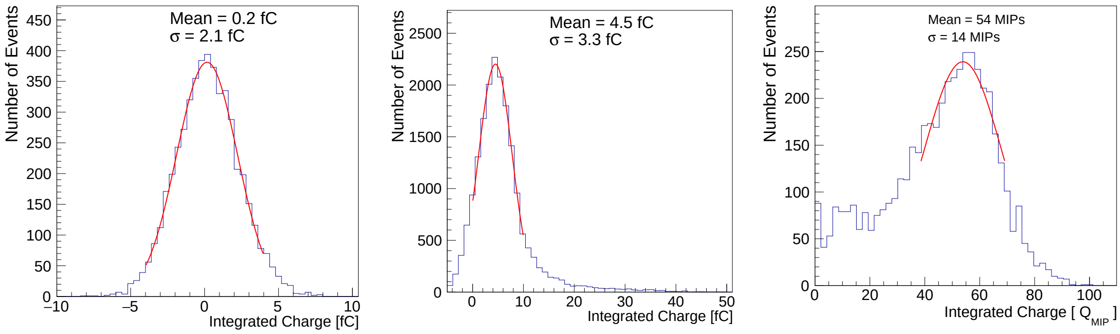

Figure 2: Measured charged distributions for signals due to pure noise (left), proton particles behaving similar to minimum ionizing particles (center), and 32 GeV electron particles after 6 radiation lengths of tungsten absorber (right).

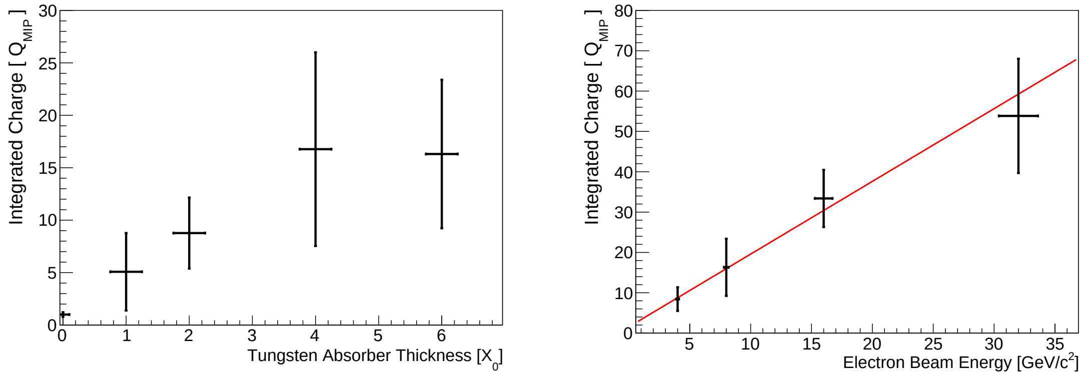

Figure 3: The mean integrated charge normalized to the charge for a minimum ionizing particle is plotted as a function of the absorber thickness (left) and the beam energy (right).

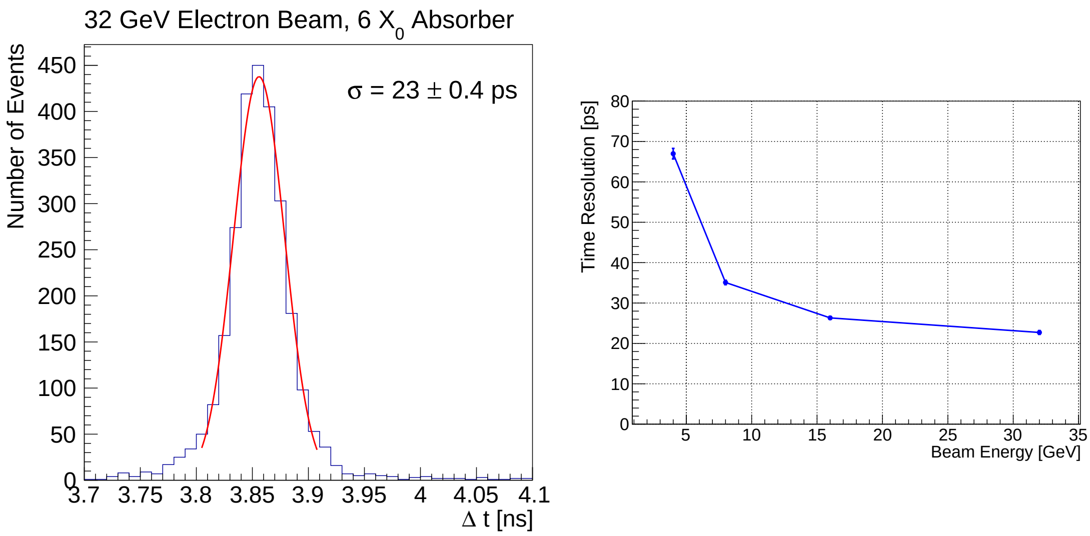

Figure 4: Left: The distribution of measured time for 32 GeV electrons after 6 radiation lengths of tungsten absorber, and its fitted width. Right: The time resolution is shown as a function of the beam energy.

where we observe that the best time resolution is achieved at the shower maximum, where the signal size is the largest. We also measured the time resolution as a function of the bias voltage applied to the silicon sensor shown on the right of Figure 5. We observe that there is a slight improvement in time resolution as the bias voltage is increased, and is attributed to the fact that a larger voltage results in a higher electric field which increases the mobility of signal electrons and holes within the silicon sensor.

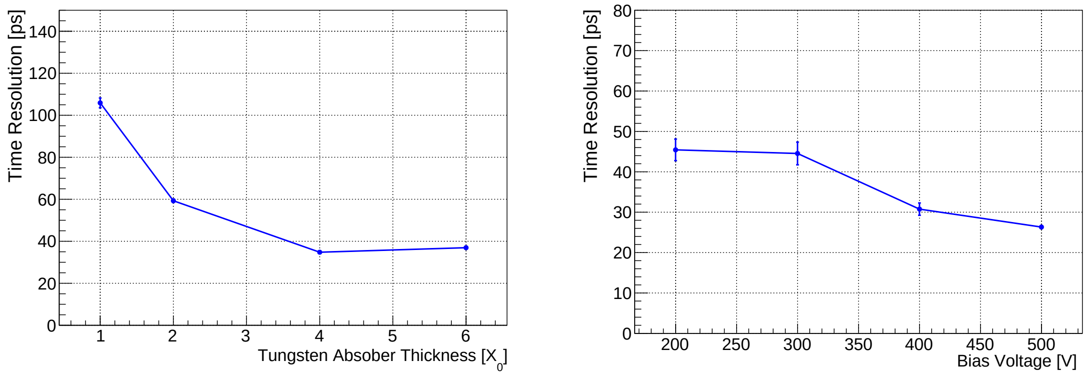

Figure 5: The measured time resolution is shown as a function of the absorber thickness (left) and the bias voltage (right).

These measurement results yield further encouragement for the use of silicon as the active layers in a sampling calorimeter and explicitly demonstrates the feasibility to use silicon for timing measurements in future calorimeters.

References

[1] Butler, J et al, “Technical Proposal for the Phase-II Upgrade of the CMS Detector”, CERN-LHCC-2015-010.

[2] Xie, S. et al, “Test beam studies of silicon timing for use in calorimetry”, NIM A Vol. 825 (2016) 62-68.

[3] Xie, S. et al, “Study of the timing performance of micro channel plate photomultiplier for use as an active layer in shower maximum detector”, NIM A Vol. 795 (2015) 288-292.