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On the timing performance of thin planar silicon sensors

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ABSTRACT

We report on the signal timing capabilities of thin silicon sensors when traversed by multiple simultaneous minimum ionizing particles (MIP). Three different planar sensors, with depletion thicknesses 133, 211, and 285 μm, have been exposed to high energy muons and electrons at CERN. We describe signal shape and timing resolution measurements as well as the response of these devices as a function of the multiplicity of MIPs. We compare these measurements to simulations where possible. We achieve better than 20 ps timing resolution for signals larger than a few tens of MIPs.

1. Introduction

Event reconstruction at future hadron colliders will be challenged by the dramatic increase in the number of concurrent interactions (pileup) per beam crossing in the experiments. At the High-Luminosity Large Hadron Collider (HL-LHC) –with up to 200 pileup events per beam crossing–, current detectors will show limitations in the reliance on purely spatial information to resolve interactions and associate particles to vertices. Moreover, the random overlap of energy deposits from neutral particles, which cannot be associated via a track to any vertex, will deteriorate the calorimeter performance in terms of energy measurement and particle identification as particles appear to be less isolated. A compact and highly granular sampling calorimeter based on silicon sensor technology has been chosen to replace the end-cap calorimeter in the CMS experiment at the HL-LHC [1]. Precision time measurement of the energy deposits could provide an additional means to resolve interactions by exploiting the spread in the time domain of the collision vertices predicted to be about 150 ps RMS, within the 25 ns bunch crossing structure of the colliding beams at the HL-LHC [2].

The silicon trackers have played crucial roles in many experiments because they afford excellent spatial resolutions at high rates and are robust. There are also a handful of examples of sampling calorimeters based on active silicon sensors. The SICAPO collaboration studied salient features of electromagnetic calorimeters with layers of high-Z absorber and silicon sensors for what were then future colliders [3]. The ALEPH and OPAL collaborations employed luminosity calorimeters consisting of tungsten and silicon sensors [4,5]. The CALICE collaboration has been investigating high-granularity calorimeters with different types of active elements as well as silicon for precision physics at future colliders [6]. In recent times, silicon sensors have also been used for timing applications in high intensity environments. The NA62 Gigatracker is one example [7]. In a beam with a flux reaching 1.3 MHz/mm^2, they have achieved single-hit timing with 200 ps RMS resolution.

In this paper, we report on the results of our first study with small planar sensors with focus on their precision timing capability, in particular for the case of multiple particles impinging simultaneously on the sensors. The shower develops extremely rapidly to be considered simultaneous: for example, the simulation suggests ~0.16 ps RMS in shower development time for 50 GeV electrons in 4 X_o absorber. We briefly describe the experimental setup in Section 2 and discuss the pulse shape reconstruction and single minimum ionizing particle (MIP)

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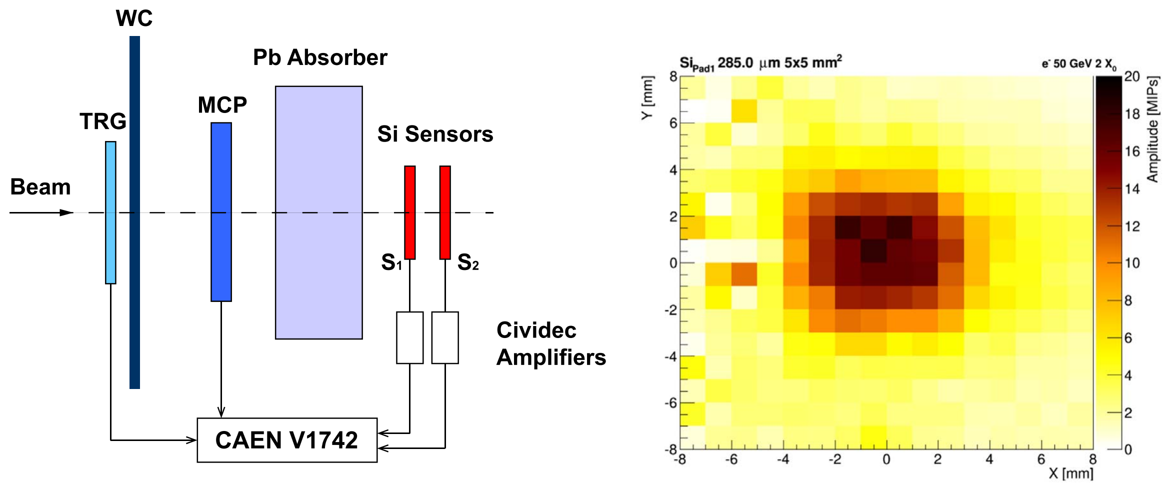

Fig. 1. The schematic of the layout displays the main components and the readout scheme on the left. Downstream of the trigger counter (TRG) and wire chambers (WC), a micro-channel plate (MCP) photomultiplier tube was positioned to provide a timing reference in front of the silicon sensors. Various lead plates were placed in between the MCP and the sensors to evaluate their response to multi-MIPs. A typical response pattern of a 285-µm thick silicon sensor (5×5 mm^2) to 50 GeV electrons when normalized to the MIP signal is displayed on the right. Note that the sensors were placed behind $2X_0$ of lead absorber in this case.

calibration in Section 3. We present multi-MIP response of the sensors in Section 4 and evaluate the timing resolution in Section 5 in some detail.

2. Experimental setup

The test setup is shown in Fig. 1. Two silicon sensors were installed in the beam line at all times. A micro-channel plate (MCP), viewing a Cherenkov radiator, provided a precise timing reference for each event within ~20 ps, with full efficiency for single MIPs at −2750 V [8]. A scintillator counter (2×2 cm^2) upstream of the detectors defined the area of triggered events. The impact position of particles on the sensors was estimated by projecting the hit positions, with better than a millimeter resolution, obtained from a set of delay wire chambers (Fig. 1). Lead sheets with different thickness were positioned in front of the sensors to generate electromagnetic showers to be able to investigate the multi-MIP response of these sensors.

The measurements described in this paper were performed at the H2 beam line of the super proton synchrotron (SPS) at CERN in July 2015. 150 GeV muons and 50 GeV electrons were used for the majority of the measurements. The beam particle intensities were typically several thousand per spill. Each spill lasted 4.9 s and was repeated twice a minute for most of the data taking period. Although the beam spot size on the sensors varied slightly with the beam tune and settings, the FWHM was about 1 cm in horizontal and vertical directions – larger than the sensors (Fig. 1).

All tested sensors were *p*-type (*n*-on-*p*), 5×5 mm^2 in the effective area and physically 32. µm thick. They were biased at 600 V and fully depleted. They were produced by deep-diffused float-zone (dd-FZ) technique by Hamamatsu within the framework of the CMS tracker upgrade project in three different depletion thickness: 133, 211, and 285 µm with capacitances of 22.5, 13.6, and 9.9 pF, respectively [9,10]. The radiation effects on these sensors are currently under study; however, none of the sensors used here was previously irradiated.

The electrical signals from the sensors were amplified by a broad-band (2 GHz/40 dB) amplifier,[1] and the waveforms were digitized at 5 GHz by a Domino Ring Sampler (DRS) unit from CAEN (V1742). The signals from MCP and the event trigger were also fed to the same digitizer unit in order to remove trigger jitter off-line. The intrinsic timing resolution of the digitizer was ~5 ps and did not contribute to the systematic uncertainty of our measurements in any significant way [11].

[1] CIVIDEC Instrumentation, C2 Broadband Diamond Amplifier, Vienna, Austria.

3. Pulse shape and MIP calibration

The rise-times from 10% to 90% of the pulse amplitude for the three sensors were measured to be 1.1 ns (Fig. 2). The pulse time was defined as the time when the pulse reaches its 50% amplitude. The offline algorithm searched for a pulse in the data stream, fitted its peak with a Gaussian function requiring at least 5 samples, and calculated the time at which the pulse reached its half amplitude.

We measured the responses of the three different type of sensors to single MIPs. A 50 GeV electron beam was used to perform this measurement. Without the lead plates in front of the sensors, 50 GeV electrons were effectively equivalent to MIPs. The results of the calibration with electrons have been found to be in agreement with the ones obtained using a 150 GeV muon beam. We selected events with a signal from the MCP and from the second sensor. The presence of a signal in the second sensor ensured that most tracks did pass through the first sensor whose response was being measured. The signal from the first sensor included a correction for a 20% noise

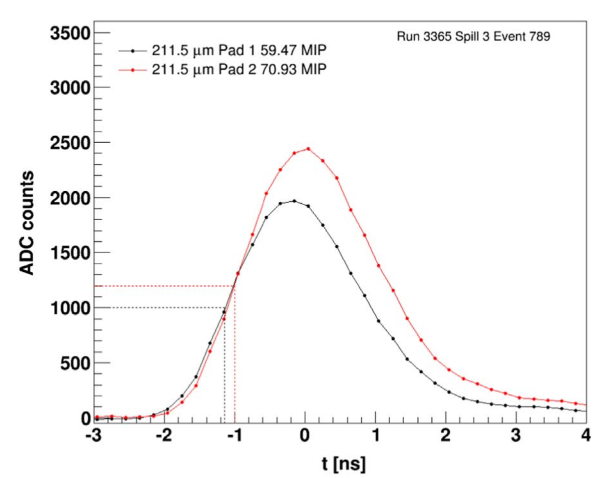

Fig. 2. Examples of single pulse shapes from two 211-µm thick sensors for the same event are shown on the left. 50% of the peak amplitude is indicated by dotted lines and is used in all the timing measurements discussed in Section 5. The peak of the pulses is arbitrarily set at t=0.