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The development of a laser system for use in the timing performance measurements of CMS HGCAL silicon modules

F.A. Khan,[a,b,*] M. Noy,[a] A. Steen,[a] F. Monti[a] and S. Ganjour[c] on behalf of the CMS collaboration

[a] *CERN, 1211 Geneva 23, Switzerland*
[b] *ULB, Av. Franklin Roosevelt 50, 1050 Bruxelles, Belgium*
[c] *IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France*

E-mail: Fakhri.Alam@cern.ch

Abstract: For optimal operations in the high radiation and pileup environment of the HL-LHC, the CMS-HGCAL requires precise timing information at the level of 30 ps (RMS) for a particle shower. The time measurement in silicon detector modules is performed using a per-channel time-of-arrival discriminator coupled with charge measurement to correct for the time-walk. The module design includes access holes in the PCB and in the sensor passivation to enable infrared laser light to be injected directly into the sensor cells. We present the calibration and timing-in of the system used to perform measurements.

Keywords: Front-end electronics for detector readout; Calorimeters; Lasers

*Corresponding author.

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2024 JINST 19 C03023

Contents

1 Introduction

The Large Hadron Collider will enter the High Luminosity phase of operations in the last quarter of this decade. High radiation levels and a large pile-up (on average of 200 collisions simultaneously) will be major challenges for the HL-LHC operations [1]. Studies show that there will be a spread of interaction vertices in position of approximately ±50 mm along the beam axis, and in time of approximately ±150 ps. Detector simulation studies indicate that the physics potential can be improved by mitigating event pileup through time-tagging events with a precision of ∼30 ps (RMS) [2]. To cope with all these challenges, the present CMS endcap calorimeters, ECAL and HCAL will be replaced by the new High Granularity Calorimeter (HGCAL). The HGCAL, a 47-layer sampling calorimeter, comprises two parts: CE-E (Electromagnetic) and CE-H (Hadronic). In CE-E, copper and lead serve as absorbers, while silicon functions as the active material. On the other hand, CE-H utilizes stainless steel as an absorber, employing silicon in high radiation regions and plastic scintillator tiles readout by SiPM (Silicon Photomultiplier) in areas with low-radiations [1].

Both endcaps of the HGCAL will be instrumented with ∼ 28000 silicon Hex-Modules, which tile together to form cassettes as shown in figure 1. A CE-E cassette is 1/6$^{\text{th}}$ of a layer, while in the CE-H region it is 1/12$^{\text{th}}$ layer due to the larger size. The silicon Hex-Modules are designed for the electronics specifications of measuring charge from a silicon sensor with a large dynamic range (0.2 fC to 10 PC) and the time of arrival with accuracy better than 100 ps. To characterize a silicon module, we have developed a pulsed laser based test system with precise timing and charge injection capabilities. A detailed description of the laser system and the timing-in procedure, as well as the performances of both the laser system and the silicon module will be presented.

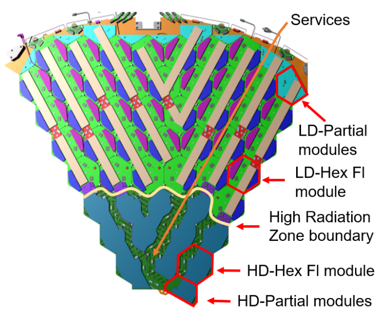


Figure 1. CE-E Cassette instrumented with various types of silicon Hex-Modules (Fl: full and partials).

2024 JINST 19 C03023

2 Silicon Hex-Module

A silicon Hex-Module (generally referred to as a silicon module) is constructed from a glued assembly of a rigid thermally conducting base-plate, a Kapton$^{\text{TM}}$ laminated copper foil, a silicon sensor, and the hexagonal readout PCB (Printed Circuit Board) known as Hexaboard, as shown in figure 2 (left). The Hexaboard is a complex eight-layer readout PCB equipped with multiple HGCROC ASICs [3, 5]. Hexagonal Silicon sensors are diced from 8″ wafers and come in three active thicknesses: 120 µm, 200 µm and 300 µm, with two hexagonal diode pad sizes: High Density (HD) = 0.51 cm^2 and Low Density (LD) = 1.18 cm^2. To increase the coverage at the inner and outer peripheries, partial silicon modules have been designed, introducing a total of 11 silicon module variants [3]. The baseplate for the CE-E region is made from a CuW (75:25) (Copper-tungsten) alloy to increase the radiation length of the CE-E absorber. For the CE-H modules, this aspect is deemed unnecessary, and the baseplate is made of cost-effective carbon fiber material. It has compatiable thermal conductivity (TC) and Coefficient of Thermal Expansion (CTE) characteristics as CuW and possesses ample mechanical rigidity to offer the required structural support. The Kapton foil provides electrical insulation for the sensor back-plane from the baseplate as well as forming a noise shield for the sensor. The HGCROC is a radiation-hard ASIC developed for HGCAL as the readout chip [4]. It has 72 analog channels; each channel has an ADC (analog-to-digital convertor) and two time-to-digital converters (TDCs) to measure both the TOA (time of arrival) and TOT (time over threshold), as shown in figure 2 (right). The ADC is used for reading charges from a silicon pad up to 160 fC–190 fC (for a typical 160 fC ADC range), while the TOT reads charges above those saturating the pre-amplifier, up to 10 pC. The TOA discriminator is used to measure the time of arrival for a signal with charge greater than 50 fC. The silicon module used for this study is made of 300 µm thick n on p silicon sensor and with a typical operating bias voltage of −280 V.

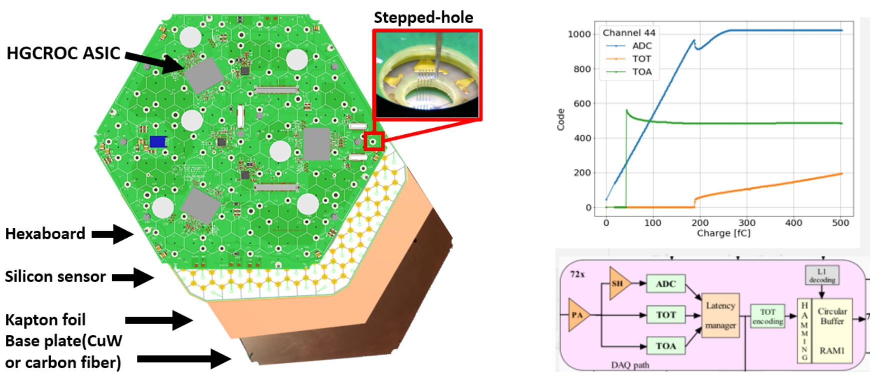


Figure 2. (Left) Silicon module: glued assembly of base plate, kapton foil, silicon sensor and Hexaboard, where sensor cells are bonded to the pads on Hexaboard through stepped-holes. (Right) Internal block of a single channel including ADC, TOT, TOA TDCs and their output vs input charge.

3 Laser system for silicon module characterisation

The test system developed for the silicon module characterisation uses a 1064 nm pulsed laser-diode having a very narrow 100 ps FWHM (full width at half maximum) pulse, offering 7 µm beam size using a microfocal lens. The test setup block diagram is shown in figure 3. The main blocks are a precise clock

2024 JINST 19 C03023

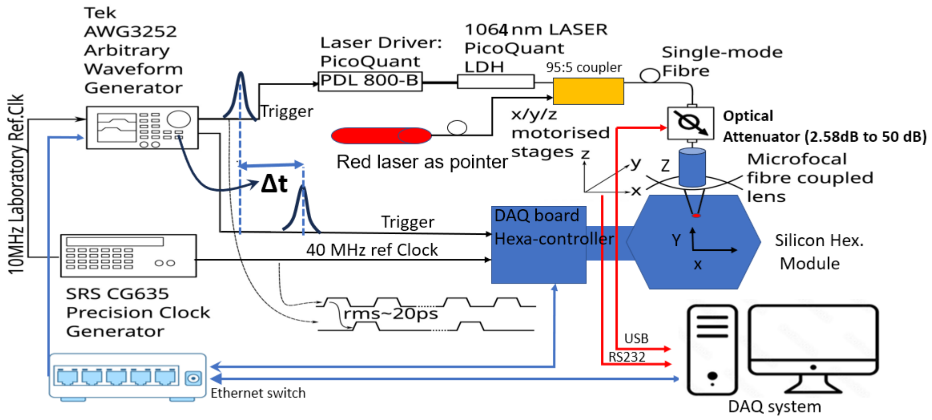
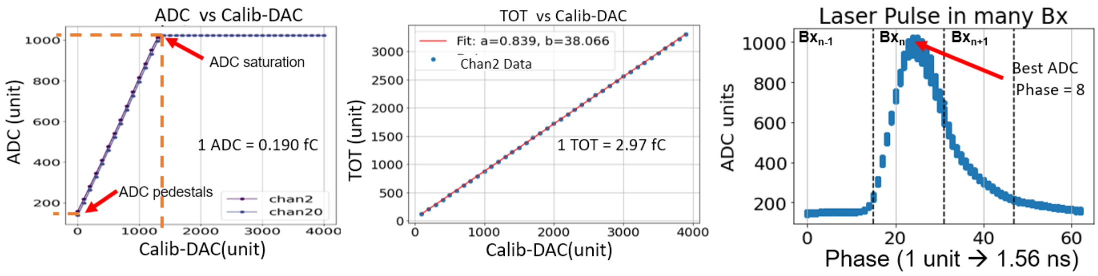


Figure 3. Laser setup: the clock source (SRS CG635) produces 10 MHz and 40 MHz for AWG3252 and DAQ boards. AWG3252 triggers Laser driver and Hexacontroller. Other Components include a Laser diode, optical coupler (95:5), optical attenuator, and scanning stages for the silicon module.

source SRS “CG635”, arbitrary waveform generator “AWG3252”, Laser driver “PicoQuant’s PDL-800B”, Laser diode “PicoQuant LDH”, optical attenuator, 3 x Zaber stages for x, y, z movements, and the silicon module with Hexacontroller (DAQ board). The SRS CG635 works as a master clock source to keep all parts of the system in the same phase, generates two clocks: one 10 MHz laboratory reference clock going to waveform generator AWG3252 and a 40 MHz for Hexacontoller. The AWG3252 generates two trigger pulses with a programmable relative delay and repetition frequency of 10 kHz, phase-locked to the reference clock. One is used to trigger the Laser driver, producing an optical pulse transmitted through the single mode optical fiber passing through the optical coupler [95:5], optical attenuator and is focused into the center of silicon sensor cell via the microfocal lens. The second trigger is sent to the Hexacontroller to open the acquisition window. The Δt between the two triggers is tuned to a value such that the Hexacontroller acquisition window opens at the time when the laser impinges on the silicon sensor. Moreover, a computer-controlled optical attenuator has been integrated to fine-tune the laser signal’s amplitude, with an adjustable range from 2.58 dB to 50 dB, with a step of 0.01 dB. Additionally, the incorporation of precision xyz-motion stages facilitates the automated scanning of the silicon cells across the entirety of the silicon module. The setup has been fully automated using Python scripts running on the DAQ PC, which connects the waveform generator, Hexacontroller via Ethernet while communicating with the optical attenuator, and x, y, z stages through USB and RS232 protocols, respectively. This automation includes all testing procedures which involve processes like aligning the laser with the center of the silicon cell, adjusting the delay on the waveform generator, triggering the laser, changing attenuation settings, and data acquisition through the Hexacontroller. The silicon module was biased with −280 V and all data were recorded at room temperature and in a dark environment.

3.1 Charge calibration

The HGCROC has a per-channel electronic charge injection circuit, allowing programmable charge injection at the pre-amplifier input from 0.25 fC up to 10 pC. From this circuitry, the ADC and TOT conversion factors were measured to be 0.190 fC / ADC-LSB, and 2.97 fC / TOT-LSB respectively. These curves are shown in 4(a, b). Using these conversion factors, the charge injected by the laser system as a function of the attenuator setting was determined.



(a) ADC vs Calib-DAC (b) TOT vs Calib-DAC (c) ADC phase scan across Bxs

Figure 4. Plots (a) and (b) display ADC and TOT calibration via internal charge injection. Plot (c) demonstrates ADC variation across four bunch crossings, where an externally laser injected pulse is reconstructed to find best phase and right bunch crossing.

A charge profile, representing the Laser injected (reconstructed) charge as a function of the attenuation value, is produced by an automated Python script. Initially, the laser is accurately aligned with the hole in the center of the Hexaboard cell using x, y, and z stages as shown in figure 5 (right). Subsequently, the script varies the attenuation values from 50 dB to 2.58 dB and acquires both the ADC and the TOT values for all attenuation settings. These ADC and TDC codes are then transformed into charges using the factors extracted in the internal calibration process. The charge profile, presented in figure 5 (left), reveals that the ADC begins to detect charge at ~ 29 dB and gets saturated around ~ 13 dB. Beyond this point, charge measurements are carried out by the TOT, covering a range of up to 2400 fC, which corresponds to ~700 MIPS (Minimum Ionizing Particles).

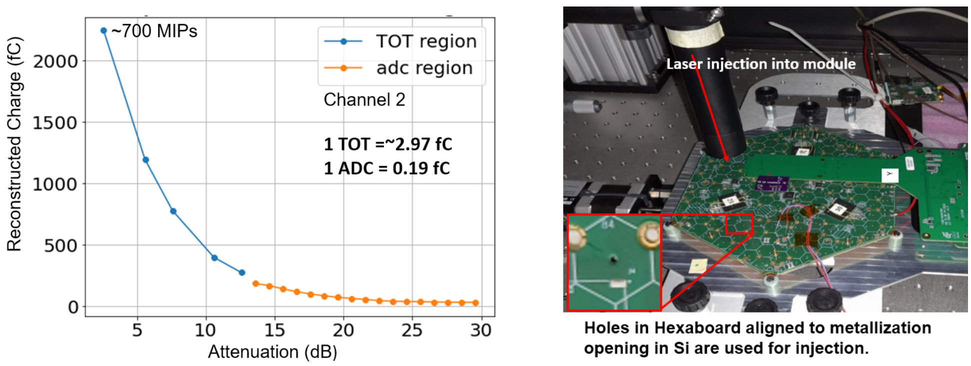


Figure 5. Left: charge profile — injected charge vs. optical attenuation (dB) for channel 2 of the silicon module. Right: image of the silicon module under test, with the injected laser signal.

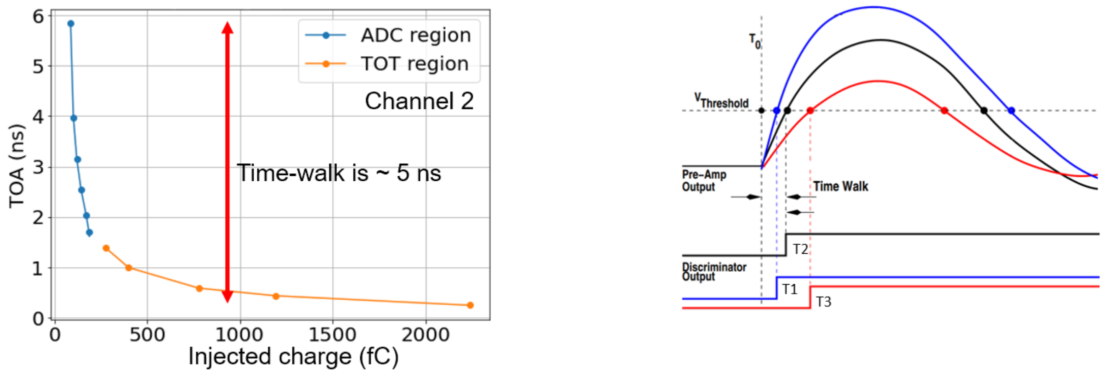
3.2 Time synchronisation

The laser was shined in the silicon module cell with a fixed attenuation of 13.58 dB and a trigger time phase-locked to the reference clock. This made sure that the pre-amplifier response was in the ADC range. The HGCROC has a per-channel DLL (Delay Locked Loop) allowing the ADC sampling phase to be swept in 16 steps through the 40 MHz reference clock. By sweeping this setting in combination with the bunch crossing, in which the trigger signal was generated, the full pre-amplifier response was sampled across four bunch crossings. From plot in figure 4(c), the optimal ADC sampling phase and right bunch crossing for the trigger were selected.

2024 JINST 19 C03023

3.3 Time-walk study of silicon module

Time-walk phenomena can be defined as the dependence of measured time intervals of incoming signals or events on the amplitudes or shapes of the signals. Figure 6 (right) explains time-walk using three input signals of differing amplitudes, originating from the same time T_0. The signal with the largest amplitude has a faster slew rate, and thus crosses the threshold earlier than the signals with lower amplitudes. Therefore, all three signals with different amplitudes register different discriminator times of arrival T_1, T_2 and T_3 [6]. For the time-walk study, we adopted the same procedure of injecting laser light as explained in 3.1. Figure 6 (left) shows TOA as a function of injected charge for both ADC and TOT regions of channel 2. A time-walk of approximately 5 ns pk-pk is measured. To provide timing information at the 100 ps level, a charge-based correction must be implemented, and this is currently under study.



(a) Time-walk for Channel 2.

(b) Effect of signal amplitude on discriminator output

Figure 6. Left: TOA vs. injected charge. Right: three signals arriving at T_0, crossing the threshold at varying times due to different amplitudes, resulting in distinct arrival times T_1, T_2, and T_3.

4 Conclusion and outlook

A laser based test setup with precise control over charge and light injection position, offering a clean environment for the silicon module characterization, was developed and calibrated. A timing study was performed for a single channel of the silicon module, and we observed a time-walk of 5 ns necessitating to be corrected using the charge information. The next step for outlook is to extract the time resolution of a channel for a silicon module from the time-walk study. At present, the other factors contributing to the silicon module's jitter, such as uncalibrated TDCs, Laser jitters, and the silicon module reference clock jitter are currently under study. After subtracting these contributions in quadrature, we will have the real-time resolution value for the silicon module channels.

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2024 JINST 19 C03023

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2024 JINST 19 C03023