# Time Measurement Calibration of **HGCAL** Prototype Modules

SUMMER STUDENT PROGRAM 2019

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# I. Introduction and Context

During the first run of the Large Hadron Collider (LHC)[1] between 2010-2012, the accelerator operated at 8TeV, and the data collected lead to the discovery of the Higgs boson. Run 2 took place between 2015-2018, and detailed studies are still being carried out on the Higgs boson and Standard Model (SM) processes as well as searches for physics beyond the SM. After the third long technical shutdown scheduled for 2024-2026, the High Luminosity-LHC (HL-LHC) operational phase will commence in the last quarter of 2026. The HL-LHC will integrate ten times more luminosity than the LHC, posing significant challenges for radiation tolerance and for dealing with the so-called pileup events for detectors in which the collisions happen. This is especially true for calorimeters in the forward region. Indeed, in high-luminosity colliders, a single crossing between 2 bunches of protons can produce several separate events, so-called pileup events with respect to the interaction of interest. With the increase in luminosity in 2026, the expected pile up will be in average 200, which is orders of magnitude higher than it is now at 40.

As part of its HL-LHC upgrade program, the CMS Collaboration[2] is proposing to build a high granularity calorimeter (HGCAL) to replace the existing end-cap calorimeters. It must have the ability to withstand integrated radiation levels that are ten times higher than anticipated in the original CMS design. In addition, one of the main requirements for the HGCAL upgrade, is the time precision measurement of the high energy showers. It is important to obtain precise timing from each cell with a significant amount of deposited energy, aiding rejection of energy from pileup, and the identification of the vertex of the triggering interaction.

Prototype modules for the future detector, have been constructed, based on 6-inch hexagonal silicon pad sensors. In 2017 and 2018, beam tests of different sampling configurations were conducted with the prototype modules: at DESY using electron beams and at CERN using beams of charged hadrons, electrons and muons.

# II. Time of Arrival (ToA)

## II.1. ToA measurement with the prototype

The prototype modules (**FIG.1.**) used in the beam test mentioned are not yet the final design for the detector. These modules have 4 readout chips SkiRoc2-CMS[3], serving 64 channels whom 32 are connected to silicon pads. This chip measures the timing in a very specific way via the time of arrival (ToA). This measurement characterizes the time at which the charge was deposited in a sensor.

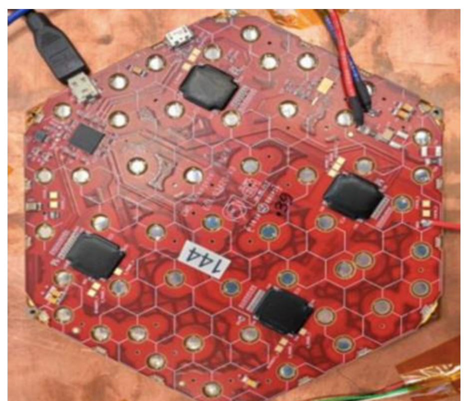


**FIG.1. Prototype module.**

**FIG.2.** displays the pulse shape line of a charge deposited as a function of time.

When the amplitude of the charge exceeds a certain programmable threshold, the ToA measurement in ADC count is triggered with respect to the 40 MHz LHC clock.

As shown in **FIG.3.**, the ToA rise and ToA fall are measured from the trigger, skipping the first clock edge (be it ascending or descending), until the next rising or falling edge respectively.

### II.2. Time Walk

The ToA depends on the energy of the incoming particle and introduces a shift in the triggering time. This effect is called time walk.

As shown in **FIG.4.**, signals injected at the same time, but with different charge amplitudes, reach the threshold at different times. This problem is faced by all systems measuring the time with the ToA, like the beam test at CERN in October 2018 (hereafter referred to as "the beam test"). Therefore the ToA measurement should be corrected for this effect. This can be achieved by performing the calibration at several charge amplitudes.

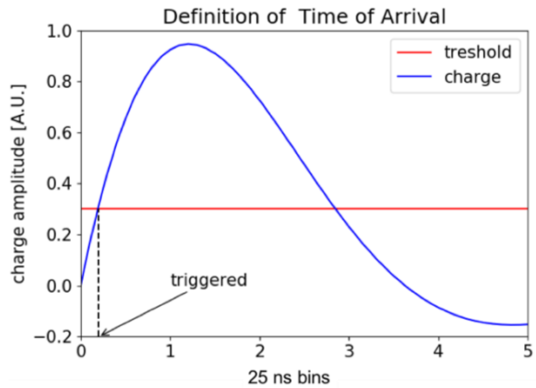


**FIG.2. Charge signal as function of time.**

### II.3. Beam test and laboratory measurements

For the beam test, the modules were disposed in layers consisting of either one single centered module or a "daisy" of 7 modules.

The data were acquired for beams of electrons, muons, and pions, for a wide energy range (between 30-200 GeV). Time calibrations were performed in a second time from these data.

However as the beam was concentrated in the center of the layers, only the channels of modules exposed to the longitudinal electromagnetic shower maximum received enough charges to be calibrated. Besides, a proper calibration method can only be obtained under controlled conditions, in an environment allowing to study the effect of different variables separately.

This led to the choice of performing the modules calibration in an electronic laboratory at CERN (referred to as "the lab" in this report).

Finally, it is important to compare whether the calibration done with the beam test actually matches what happens in the controlled conditions, to get to the desired resolution for the final detector.

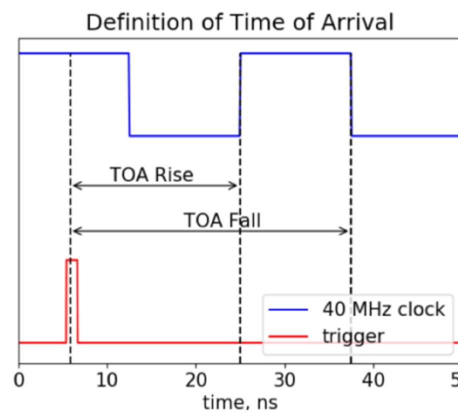


**FIG.3. Signal with respect to the 40 MHz clock.**

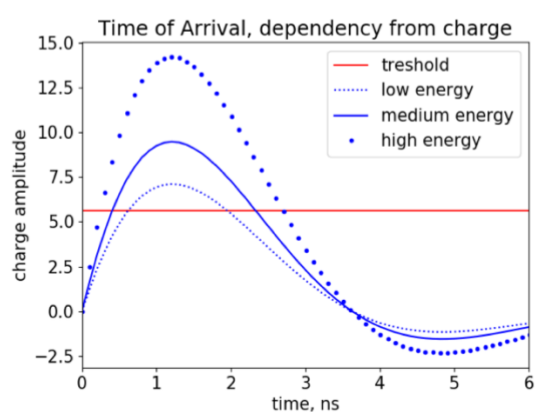


**FIG.4. Time-Walk effect.**

## III. Experimental Laboratory Measurements

For a proper comparison with the beam test four modules located in the electron beam shower maximum were chosen, and only the channels fully calibrated will be considered.

The module IDs are 69, 32, 79, and 83; and they had in average 70 calibrated channels out of 128 after the beam test.

The experimental setup is shown in **FIG.5.**. The individual module are placed inside a temperature controlled box (1) supplied by a cooler (2) where the temperature was controlled to 1°C accuracy.

To perform the calibrations, a test stand board, controlled by a Raspberry-Pi3 is used. It can be seen on top of the temperature-controlled box in **FIG.5.**.

For the ToA calibration, the data acquisition is performed according to the following steps that one can follow on **FIG.6.** :

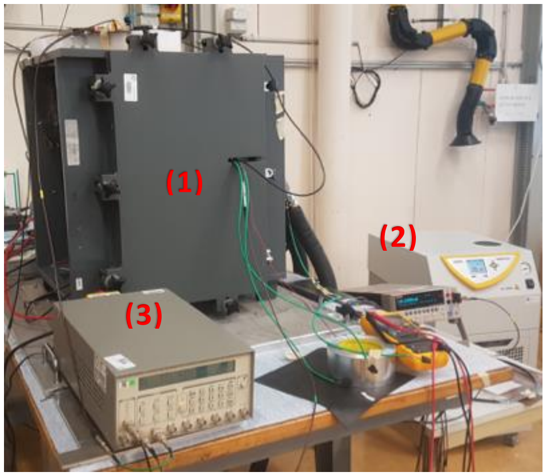


**FIG.5. Laboratory Setup.**

- the test stand board sends a signal to the front-end ASICs to start their acquisition

- the test stand board sends a trigger to a delay generator (Line 1.)

- the generator waits during a programmable delay and sends a pulse charge to the module, and the pulse is then sent to its channels (Line 2.)

- after an extra delay, the generator sends a trigger signal to the test stand board and this signal is sent to the module (Line 3.)

- when the trigger signal is received by the module, the acquisition is paused to perform the data read-out.

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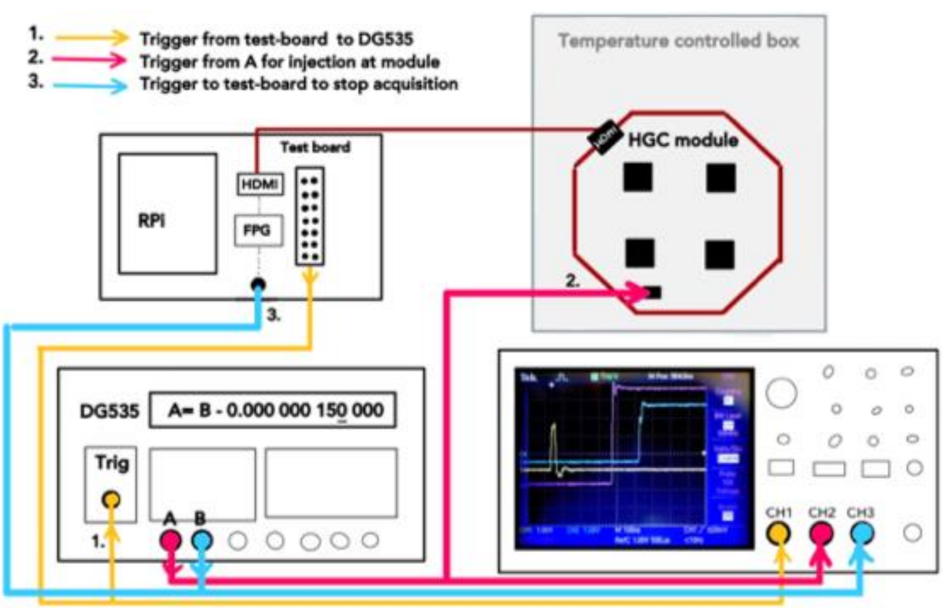


**FIG.6. Experimental Scheme.**

By scanning the delay of the charge injection, the ToA data are obtained as a function of the time, and thus they can be used to calibrate the ToA.

A charge is injected into the 32 channels of each module, and 1000 events are acquired per run. Each run scans over 30 ns, with a step size of 30 ps.

## IV. Calibration Procedure

The raw data obtained are shown in **FIG.7.** displaying the ToA versus the event number for one channel of the module 69. A jump can be observed around the event 720 and results from the signal crossing the clock edge which was skipped for the ToA measurement so far.

This switch of clock cycle is identified and the data points are reordered within one clock cycle.

To get a transformation from ToA in ADC counts to real time units, the event number is linearly transformed in time.

Before obtaining a fit, the ToA is normalized to allow a uniform comparison of the results of the different channels and a graph of normalized ToA versus time is obtained as seen in **FIG.8.**.

The axes are then swapped to show the ToA time dependency and results in **FIG.9.**.

The data is fitted with a function which has a linear and a non-linear part, as suggested by the shape of the data distribution. The fit function used (1.) is the same one used for the beam test and has two free parameters:

$$delay(ToA) = \boldsymbol{c} \cdot ToA + 25 + \boldsymbol{d} \cdot \left(\frac{1}{ToA-1.25} + 0.8\right) \quad (1.)$$

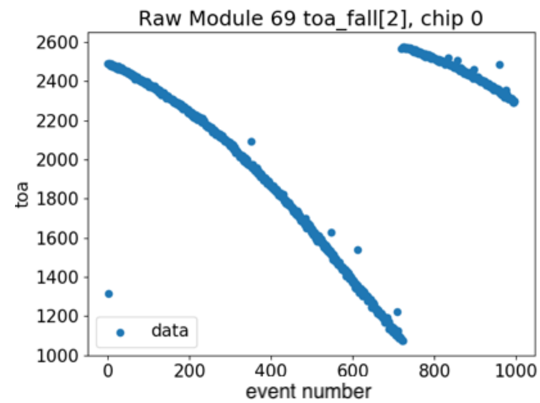


**FIG.7. Raw data: ToA as function of event number.**

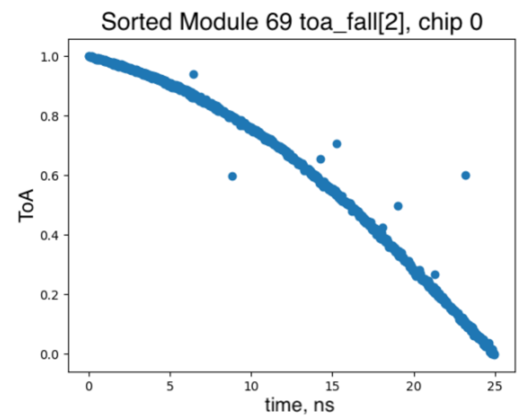


**FIG.8. Normalized ToA as funtion of time within one clock cycle.**

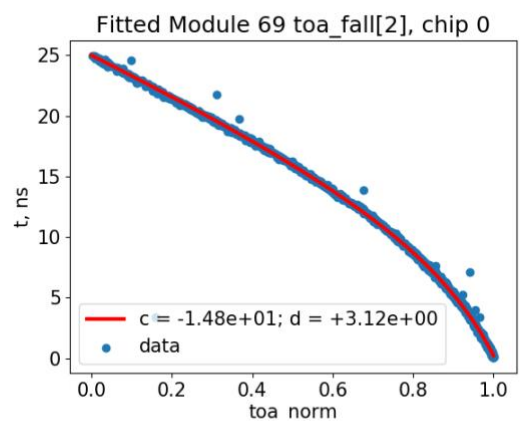


**FIG.9. Time versus normalized ToA: data and fit function.**

# V. Results Comparison

## V.1. Fit-Function Parameters

To compare the results obtained in the lab with those from the beam test, the parameters obtained from the fit function are first considered.

The following (normalized) difference variable is used:

$$\Delta_c = \frac{c_{lab\ test} - c_{beam\ test}}{c_{lab\ test}}\ .$$

The results are shown in **FIG.10.** and **FIG.11.**.

The coefficients seem to be anti-correlated which was not an expected effect.

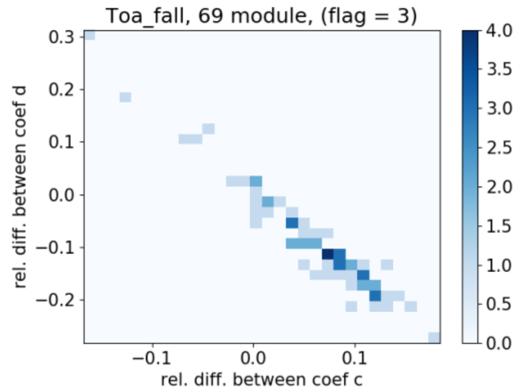


**FIG.10. 2-D relative difference between coefficients c and d for ToA-fall.**

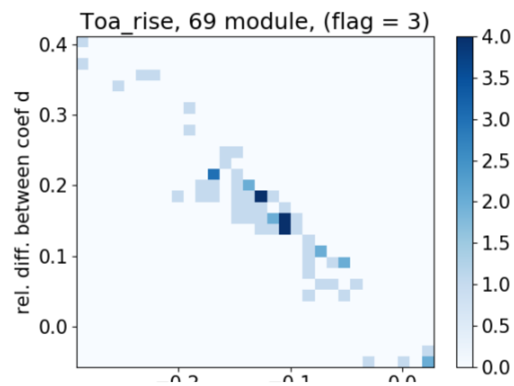


**FIG.11. 2-D relative difference between coefficients c and d for ToA-rise.**

## V.2. ToA Range

**FIG.12.** shows the obtained difference in ToA ranges (so before any normalisation) between lab test and beam-test for the module 79 The ToA range obtained in the lab is smaller than the one in the beam test.

The 2% difference roughly corresponds to a range of 500 ps in ToA units. This discrepancy was not expected and suggests further testing in order to identify the variables affecting this range.

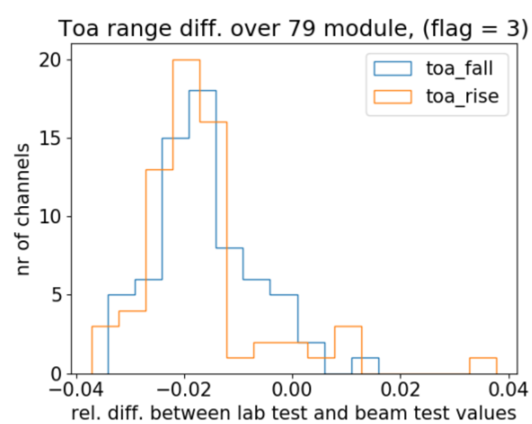


**FIG.12. Relative difference between lab test and beam test for the ToA fall and rise ranges for module 79.**

The variation of temperature is first considered. The temperature at which the measurements were taken during the beam test and the lab test was about 28ºC. In the lab, the data are acquired again at 20ºC and 36ºC. The results obtained are compared to those obtained in the lab at 28ºC, and are shown in **FIG.13.** and **FIG.14.**

The histogram in **FIG.13.** shows the relative difference for the min ToA and max ToA between two lab tests performed at 20ºC versus 28ºC.

The following normalized difference for ToA max (or min) equation is used:

$$\Delta_{\mathbf{ToA}\mathrm{max}} = \frac{ToA_{\mathrm{max}\ at\ 20º} - ToA_{\mathrm{max}\ at\ 28º}}{ToA_{\mathrm{max}\ at\ 28º}}$$

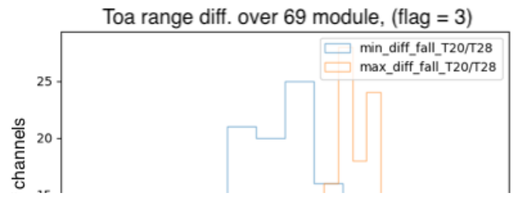

**FIG.13. Relative difference between lab tests performed at 20ºC and 28ºC for module 69.**

The histogram in **FIG.14.** shows the relative difference for the minimal value of the ToA (ToA-min) and the maximal value of the ToA (ToA-max) between two lab tests performed at 36ºC versus 28ºC.

It can be noted that the major difference appears in the ToA-min, while the ToA-max remains somehow stable with temperature variation. This is expected due to the fact that the ToA varies faster with time around the minimal value than around the maximal values, as can be seen on **FIG.8**..

But no other correlation pattern can be observed, and this suggests further testing on how the ToA range varies with several measurements under the same temperature conditions.

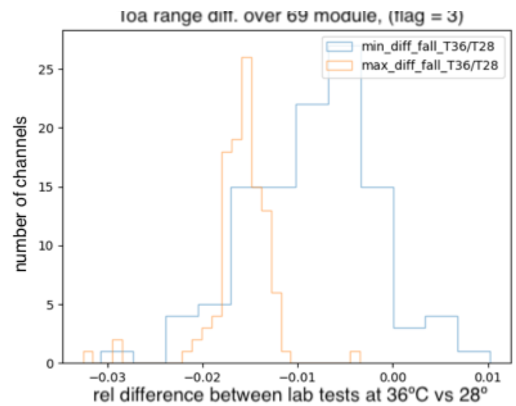

**FIG.14. Relative difference between lab tests performed at 36ºC and 28ºC for module 69.**

## V.3. Time Resolution

As already mentioned, time resolution is one of the major measurement for the prototype being tested. The readout chip used for the prototype module in the lab and in the beam test has an optimum design resolution of 50 ps.

To test this resolution in the lab, charges were injected with different amplitudes at a certain fixed delay. The time resolution can then be extracted from the width of the resulting distribution.

The results are shown in **FIG.15.** and **FIG16.** for the charge equivalent of 0.1V and 2.0V respectively, at a certain preset delay. To do not take into account the outliers data points and to facilitate the comparison of the ToA rise and fall, only the *interquartile-range* (***iqr***) was considered. The **iqr** is a measure of statistical dispersion, being equal to the difference between 75th and 25th percentiles.

For 0.1V, the *iqr* for ToA-fall (1.02 ns) is smaller than that for the ToA-rise (1.31 ns).

For 2.0V, the *iqr* for ToA-fall (0.19 ns) is greater than that for the ToA-rise (0.18 ns).

This means that depending on the point one is looking at on the delay-ToA graph, the best accuracy can be given by the ToA fall or the ToA rise.

Now considering the time resolution that is reflected in the *standard deviation* of the distribution, the results for 2.0V will be analyzed, as it is known that 2.0V corresponds to a value higher than 500 Minimum ionizing particles (MIPS).

Transforming the results obtained in *iqr* to standard deviation, the time resolution obtained is 285 ps and 262 ps for ToA-fall and ToA-rise respectively. This is far from the expected resolution of 50 ps. This poses questions regarding the timing accuracy in the utilities used in the lab setup, and suggests further studies on the clock-jitter from test-board, and step precision of delay generator.

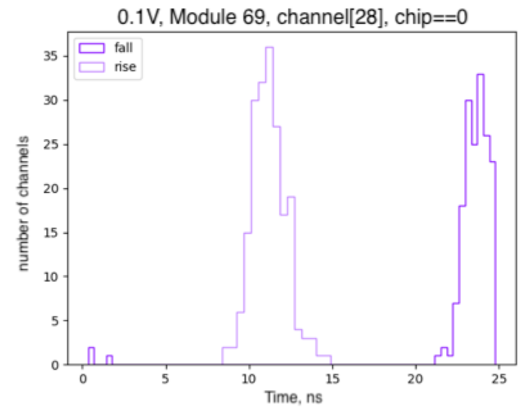


**FIG.15. ToA-fall and rise distributions at a fixed delay for charge injection amplitude equivalent of 0.1V.**

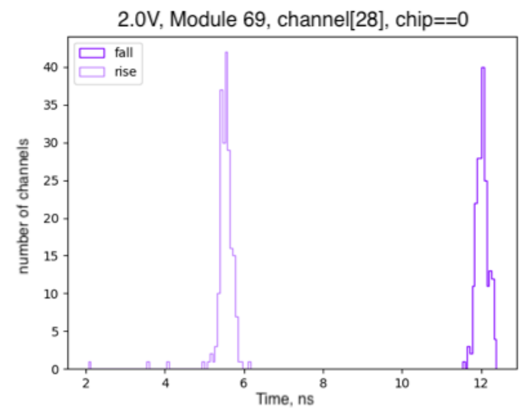


**FIG.16. ToA-fall and rise distributions at a fixed delay for charge injection amplitude equivalent of 2.0V.**

## VI. Final Note

In this work, we were able to achieve a properly documented calibration procedure for the timing measurement of a HGCal prototype module tested in the October 2018 CERN beam test.

By comparing the results obtained in the lab to those in the beam test, the technique seems promising, and through multiple tests we were able to identify different variables that interfere with the calibration. Based on this first study, work can continue in the view of a final detector ready to be install in 2026. Further studies will be concerned with time accuracy and later the time walk effect can be properly addressed.

## Acknowledgement

I would like to thank my lovely supervisor **Ludivine Ceard** for her continuous encouragement and advice she gave me throughout our work process, and being so kind in and outside working hours. I would also like to thank **Arnaud Steen** for all the effort he put in following our work, taking time to explain everything (on repeat), and for bearing with me while I learned python in the first few weeks (and at all). Not to forget **Bora Akgun** for his persistent positivity and encouragement that were there when needed, **Andre Tinoco** for his constructive comments on our work and presentations, and all other members of the **HGCal team** at **CERN**.

## References

[1] Lyndon Evans and Philip Bryant. LHC Machine. JINST, 3:S08001, 2008.

[2] The CMS Collaboration : The Phase-2 Upgrade of the CMS Endcap Calorimeter, CERN-LHCC-2017-023. LHCC-P-008. CMS-TDR-019.

[3] J. Borg et al: Skiroc2-CMS an ASIC for testing CMS HGCAL, 2017 JINST 12 C02019.