Time of Arrival calibration of HGCAL prototype modules using charge injection

Antra Gaile
Supervisors:
André David Tinoco Mendes and Bora Akgün

August 2019

1 Introduction

As of January 2019 the Large Hadron Collider (LHC) has entered its second long shutdown (LS2) and is under maintenance. During Run 2 the collision centre-of-mass energy was 13 TeV with an instantaneous luminosity of $\sim 1 \cdot 10^{34}$ cm^{-2} s^{-1}. This corresponds to an average of 40 simultaneous inelastic interactions per 25 ns-spaced bunch crossing, and these interactions are referred to as 'pileup'.

After the next long shutdown (LS3), the High Luminosity LHC (HL-LHC) will start, increasing the instantaneous luminosity of about 5 times. This increase of instantaneous luminosity is a challenge for detector radiation tolerance and for the mitigation of the extreme pileup where up to 200 collisions per bunch crossing are expected. For the detectors at the centre of which the collision happen, this increase requires material that can both be resistant to radiation and deliver precise measurements. To cope with these conditions the CMS collaboration [1] is in the middle of an extensive R&D programme to upgrade many parts of the detector, including the replacement of its calorimeter endcaps.

One of the key parameters for the new endcap calorimeter is a good timing resolution for the pileup mitigation and tracking efficiency. The CMS collaboration chose a High Granularity Calorimeter (HGCAL) endcaps to cope with these conditions [2]. At this moment the HGCAL is in the final research and designing phase, the first prototypes of silicon modules have been assembled and tested, but further upgrades will be incorporated. Module performance, including timing resolution, has been tested with beams at CERN, DESY and Fermilab, the results have been summarised in [3].

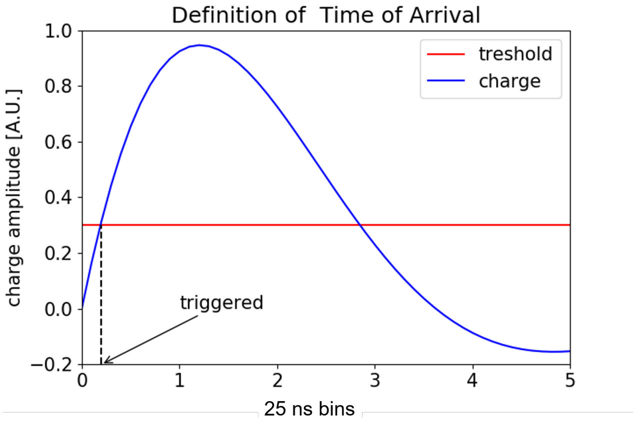


Figure 1: A deposited charge

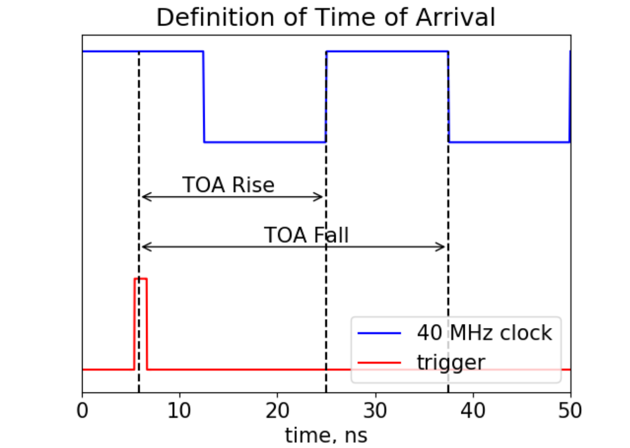
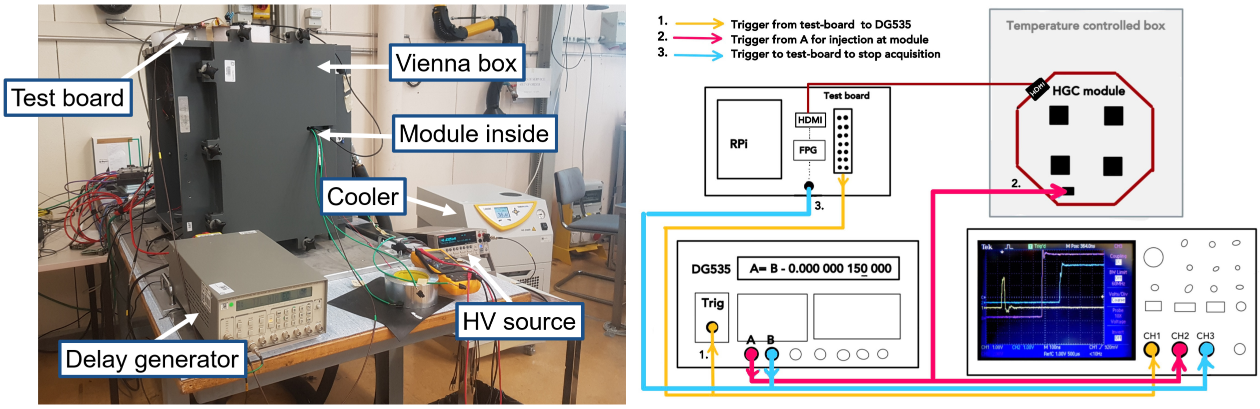


Figure 2: The definition of ToA

2 Time of Arrival measurement with the HGCAL prototype

A calorimeter prototype with 100 prototype silicon modules has been built and tested. Modules are equipped with four readout chips Skiroc2-CMS-ASIC [4]. This ASIC provides 64 channels including 32 connected to silicon pads to reduce path lengths



(a) The experimental setup of the lab test (b) The scheme of the lab test setup

Figure 3: The experimental setup

and noise. The channels have a fast shaper after the pre-amplifier, followed by a discriminator and an internal time-to-digital converter (TDC) with a 25 ps time bin. The expected time resolution for the chip is about 50 ps (for signals above approx. 12 fC).

It is easier to understand how time is measured in the HGCAL prototype through the definition of Time of Arrival. The Time of Arrival (ToA) characterises the time at which the charge deposited in a channel exceeds a certain programmable threshold (see fig. 1).

Figure 1 shows a pulse shaped line, representing the deposited charge as a function of time and a straight line to indicate the threshold. Figure 2 shows a diagram of the 40 MHz clock (used to synchronise HGCAL prototype electronics). By definition, the ToA is measured with respect to the 40 MHz clock in ADC counts from the moment the charge exceeds the threshold (see fig. 1 the straight line, in fig. 2 it is denoted as 'trigger'), it skips the first clock edge (irrespective of the type) and, depending on either we are measuring the ToA fall or ToA rise, samples until the next falling or rising edge respectively (see fig. 2).

Since the ToA is measured in ADC counts but represents a time, a conversion and calibration must be done. In the beam test that took place at CERN in Autumn 2018 (henceforth 'beam test') prototype silicon modules equipped with four Skiroc2-CMS-ASICs were used. The ToA had been calibrated with an asynchronous beam with respect to the clock, the particles arriving to the modules in a random fashion, so the ToA is sampled from a uniform delay.

Only channels with enough statistics can be calibrated. In beam tests modules that are around the longitudinal electromagnetic (EM) shower maximum can be calibrated better because most of the charge is deposited within this region. But even for these modules, not all channels receive enough particles to perform accurate calibration, therefore an alternative method of calibrating ToA must be performed.

ToA calibration can also be done in a laboratory by directly injecting charge to individual channels. The results from both calibration methods can be compared. In order to do so four modules located at electron beam shower maximum during the beam test were chosen.

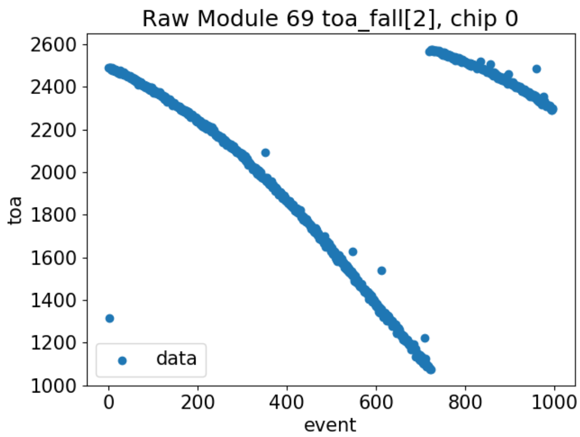
3 Experimental setup

In the lab test performed in Summer 2019 (henceforth 'lab test') an independent, laboratory-based method is used to calibrate the ToA in a controlled environment.

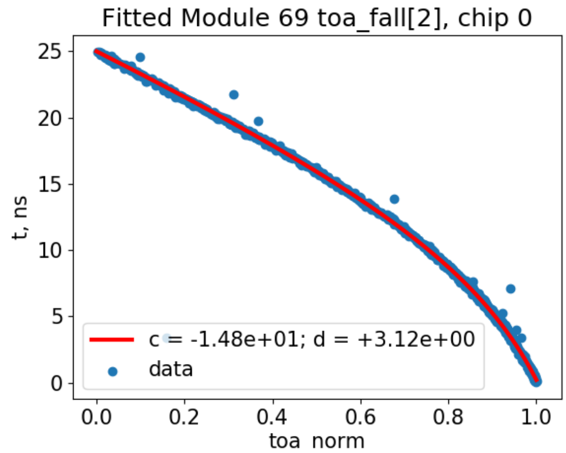
In the lab test, for each prototype module, a known charge is directly injected in each channel at a set delay and at known temperature. The experimental setup can be seen in fig. 3 (a). The module is placed inside a temperature controlled box, so-called 'Vienna box', supplied by a cooler. The test board with Raspberry Pi is situated on top of the Vienna box. The test board sends a trigger to the delay generator that generates a delay at which the charge is injected into the testing module. A scheme of the experiment can be seen in fig. 3 (b). The trigger to the delay generator is represented with line 1. The charge injection is shown as line 2, and line 3 represents the trigger to data readout (i.e. record an event).

The data is collected using a raspberry PI test board, which is represented in fig. 3 (b) by the link between the module and the test board. Lab tests were performed on four modules (ID number 32, 69, 79, 83) that were located in the maximum of longitudinal electromagnetic (EM) shower and had most of their channels calibrated in the beam test. Only channels fully calibrated in the beam test were compared with the lab test results. Injection is done in one channel in all Skiroc2-CMS-ASICs per run, each run has 1000 events and the step size of the delay between them are 30 ps, so each run scans over 30 ns, thus comfortably including one LHC clock cycle (25 ns).

The measurements are performed at $T = 28^oC$ which was the temperature beam test setup operated.



(a) Raw data



(b) Fitted data

Figure 4: An example from raw to fitted data

The injection is performed with a pulse amplitude of $1.5\ V$ which corresponds to a few hundreds of minimum ionising particles (MIPs), where the time resolution is supposed to be flat and around 50 ps.

4 Data analysis

Data analysis has been done using python3.4, explicitly using uproot, pandas, scipy, numpy and matplotlib packages.

Raw data are presented in fig. 4 (a) showing the ToA fall versus the event ID. The change of two clock cycles can be seen in the data by a sharp jump in the ToA values (see fig. 4 (a) around event 720), because at this point the ToA is measured with respect to the next clocks edge (see the definition of ToA in fig. 2). After the clock edge has been found the events are ordered and the event ID is linearly transformed into a delay.

The measured ToA range slightly differs between not only modules but also chips and channels, therefore it is normalised with respect to its minimum and maximum value to span from 0 to 1. The resulting distribution is shown in fig. 4 (b), and it must be noted that the axis has been swapped thus showing time dependency from ToA value.

The distribution is then fitted using the same formula that was used in the beam tests (1).

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

By definition, the fitting function should satisfy two fixed points, namely $t(0) = 25\ ns$ and $t(1) = 0\ ns$. It is chosen to have two free variables and to satisfy the first boundary condition. To avoid higher order terms of the parameters the fit function does not satisfy the second boundary condition, because as visible in fig. 4 (b) when $ToA = 1$, in the fit time is close to but not equal to 0.

The fit of the data gives the parameters c and d in the function and these values are later compared between beam test data and lab test data.

5 Results

The relative difference between the fit parameters estimated from the lab test data and from the beam test data, is used to compare the results (2).

$$\Delta = \frac{c_{lab\ test} - c_{beam\ test}}{c_{lab\ test}} \quad (2)$$

First, ToA ranges (the interval between the maximal ToA value and minimal ToA value) within modules are compared. In fig. 6 one can observe that within the same module the ranges of the ToA fall and the ToA rise are similar as expected. Comparing with the beam test measurement, module 32 has a ToA range measured in lab test approximately 1 % smaller. And for module 79 the ToA range measured in lab test for most channels are 2 % less than measured in the beam test. Similar differences of order of a few percent can be observed for modules 69 and 73 as well, while for module 83 the ToA range in lab test has been measured as 2 % larger. So no specific trend has been observed.

If a ToA range varies within a few percent, it directly influences the parameters of the fit formula used to approximate the data. If the ToA would be linear with time (which is not true as shown by fig. 4), a 2 % difference in ToA range would correspond to approximately 500 ps uncertainty in timing, which exceed HGCAL desired timing resolution. The difference in ToA ranges and possibly the cause of it must be further investigated.

Second, it is possible to compare the relative difference of fit parameters obtained for one module. The example of module 32 is shown in fig. 7. Fig. 7 (a) shows a 2D histogram of the relative difference of fitting parameters - coefficient c and coefficient d (see formula (1)) - for ToA fall measurements while fig. 7 (b) shows the relative difference distribution for ToA rise data.

The result indicates an anti-correlation between the relative difference between beam test and lab test fit parameters, the coefficient c is estimated larger in lab test than beam test, and the coefficient d smaller. For the ToA fall fit the coefficient values estimated in beam test and lab test agree for most of the channels. But for the ToA rise they show a greater discrepancy up to 5 %.

The three other tested modules show different relative difference distributions, for example, result for module 69 ToA fall measured in the lab test shows a 10 % offset with respect to the one of the beam test, a positive offset for coefficient c and a negative offset for coefficient d, but the ToA rise results behave in the opposite manner.

Moreover fig. 8 shows the relative difference in parameters for module 69 in fig. 8 (a) and for module 79 in fig. 8 (b). For most channels of both modules the relative differences of the fitting coefficients reach up to 10 - 20 %, which is a lot. Also, the inconsistency in differences between modules do not follow a certain trend.

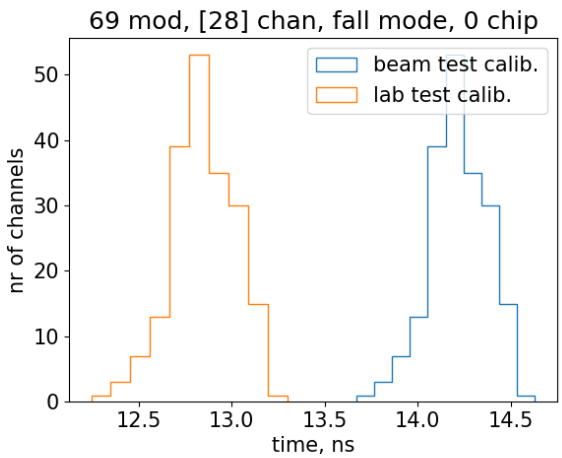


Figure 5: Time distributions obtained from one ToA measurement, using both fit data

Lastly, an additional test was performed with 200 events and the charge injected this time at a fixed delay. Since the delay of the injection was kept constant, a Gaussian distribution of ToA values was obtained. The ToA values are normalised using beam test and lab tests data for the specific module and channel. Using the formula (1) the time is calculated. Obtained distributions for one channel of module 69 is shown in fig. 5. The standard deviation of the distribution is of 150 ps and they are spaced $\sim$1.5 ns apart. It can also be seen that beam test distribution is slightly narrower since the measured ToA range is larger than in the lab tests.

6 Summary and next steps

- A new calibration method has been developed, it is lab-based and applicable for all channels of the module, by applying this method it is possible to perform dedicated studies in a controlled environment.
- ToA ranges do not agree between beam test and lab test measurements, they are off by ± 2 %.
- Strong anti-correlation has been observed for the relative differences between beam test and lab test measurements of fit parameters.

This study opens room for further investigation in particular:

- Extract time walk correction parameters by performing injection tests with varying charges.
- Study the temperature dependence.

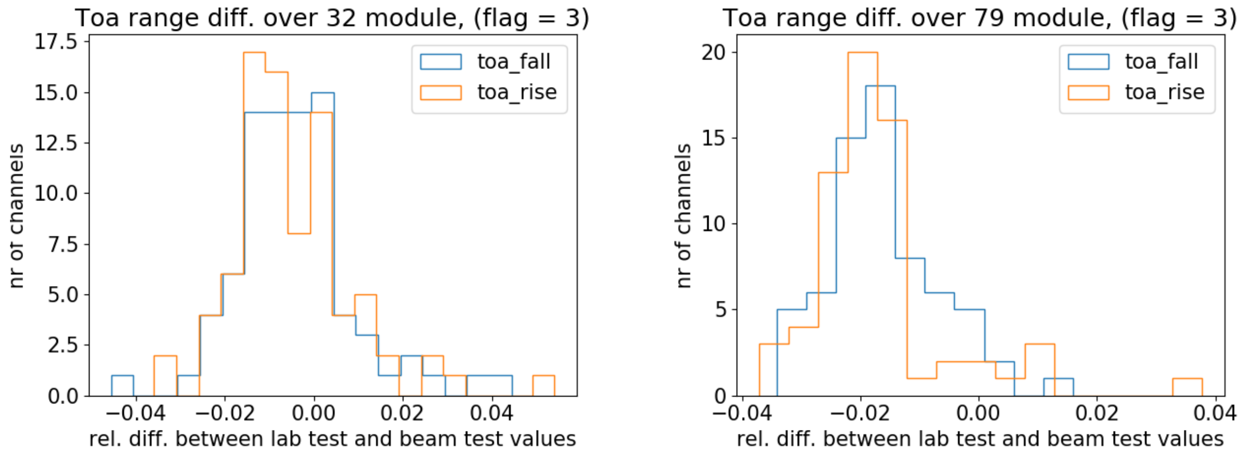
References

[1] The CMS Collaboration *et al*: *The CMS experiment at the CERN LHC*, 2008 *JINST* 3 S08004.

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

[3] N. Akchurin *et al*: *First beam tests of prototype silicon modules for the CMS High Granularity Endcap Calorimeter*, 2018 *JINST* 13 P10023.

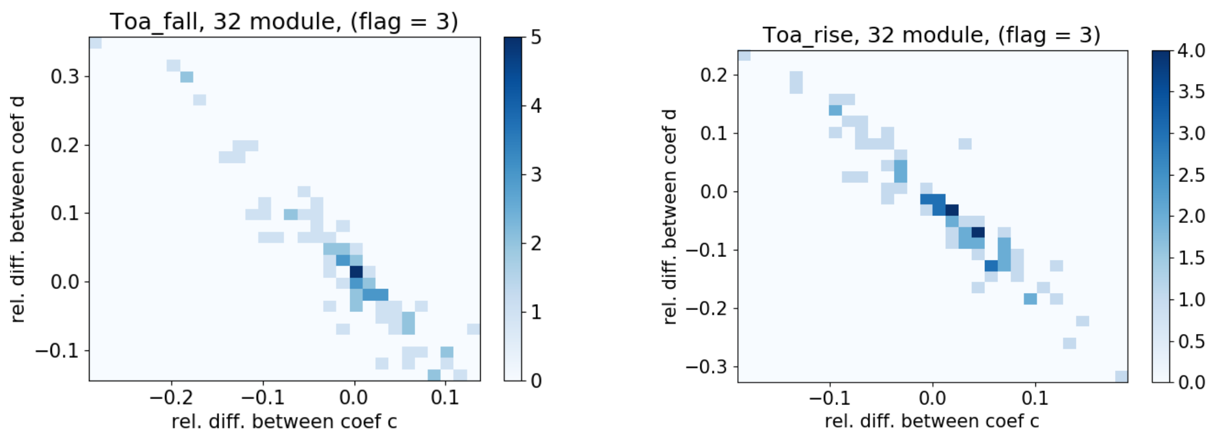
[4] J. Borg *et al*: *Skiroc2-CMS an ASIC for testing CMS HGCAL*, 2017 *JINST* 12 C02019.



(a) 32nd module

(b) 79th module

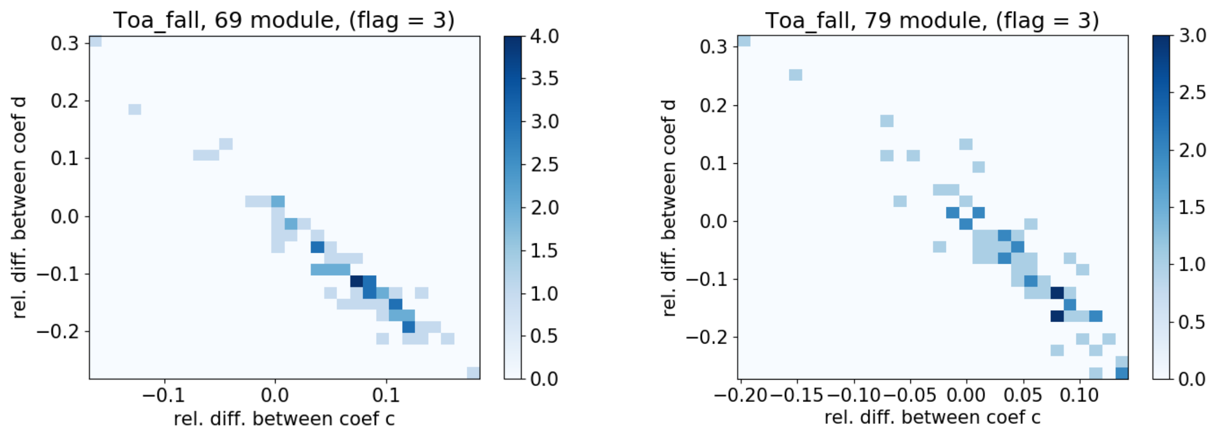
Figure 6: ToA ranges within modules



(a) ToA fall

(b) ToA rise

Figure 7: Rel. diff. of fit parameters within one module



(a) 69th module

(b) 79th module

Figure 8: Rel. diff. of fit parameters within modules