PROCEEDINGS OF SCIENCE

Qualification of macro-pixel sensor assemblies for the CMS Phase-2 outer tracker

Soham Bhattacharya[a]
on behalf of the CMS Collaboration
[a] *DESY,*
Hamburg, Germany
E-mail: soham.bhattacharya@cern.ch

The Phase-2 upgrade of the CMS detector for the high luminosity era of the LHC (HL-LHC) foresees the installation of a new tracking system to cope with the increased pileup and track multiplicity. The inner layers of the outer tracker will be equipped with pixel-strip modules that have a fine segmentation to provide an accurate position measurement. Each module contains two types of silicon sensors, a strip and a macro-pixel sensor. The pixelated sensor and its readout chip together form the macro-pixel sub-assembly, or MaPSA. A rigorous quality control procedure for the MaPSAs has been developed and validated using prototype assemblies. This report describes the qualification setup and procedure, as well as the results of measurements on the prototypes.

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1. Introduction

The CMS [1] experiment at the CERN LHC is successfully taking data with peak instantaneous luminosities up to approximately 2×10^{24} cm^{-2}s^{-1}. During the HL-LHC era, this is foreseen to increase up to 7.5×10^{24} cm^{-2}s^{-1} [2]. This will result in an increase of the average pileup from about 60 to 200 collisions per bunch crossing. As a result, the Phase-2 tracking system needs to be capable of handling the increase in pileup and particle multiplicity. Figure 1 (left panel) shows the layout of the Phase-2 tracker in the $r-z$ plane. The Phase-2 outer tracker layers will be equipped with two kinds of modules. Pixel-strip (PS) modules are to be deployed in the $200 < r < 600$ mm region, providing an accurate z (r) coordinate measurement in the barrel (endcaps). The region $r > 600$ mm region is to be equipped with two-strip (2S) modules, which provide a coarse z (r) coordinate measurement in the barrel (endcaps). Unlike in the current detector, the information from the tracker modules will contribute to the level-1 (L1) trigger in Phase-2. In order limit the volume of data that is sent out at 40 MHz, each PS and 2S module is comprised of two sensors, and is capable of rejecting tracks from particles with transverse momentum (p_T) below a certain threshold. Pairs of hits in the two sensor layers that are within a window compatible with the trajectory of a charged particle in a transverse magnetic field of 3.8 T, are selected as “stubs", which are used to build tracks at the L1 track finder. This is known as the “p_T module" concept, and is illustrated in Fig. 1 (right panel).

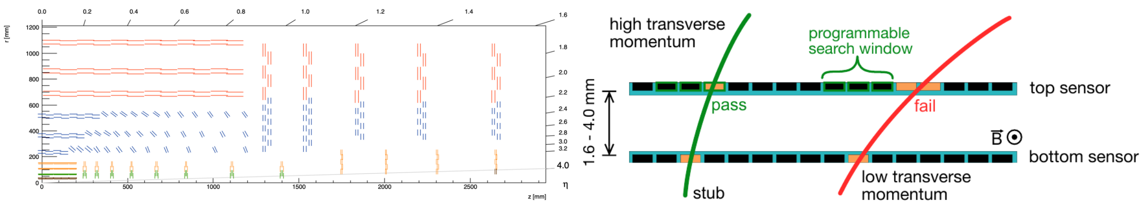

Figure 1: Left: sketch of one quarter of the Phase-2 tracker layout in the $r-z$ plane [2]. The blue and red lines represent the PS and 2S modules, respectively. Right: sketch of the p_T module concept [2].

2. The macro-pixel sub-assembly

The PS module is equipped with a strip sensor (PS-s) and a macro-pixel (PS-p) sensor. While the PS-s has strips of 2.5 cm in length, the PS-p is more finely segmented to provide an accurate z (r) coordinate measurement in the barrel (endcaps). The PS-p sensor and its readout chip (the macro pixel ASIC, or MPA) constitute the macro-pixel sub-assembly (MaPSA). Figure 2 (left panel) shows the different parts of the PS module. Each macro-pixel has the dimension 1467×100 μm^2 except the edge pixels, which are 1467×200 μm^2. The PS-p sensor is bump-bonded to 16 MPA chips, each of which reads out 1888 pixels arranged in 16 rows and 118 columns. A cross-section view of the MaPSA relative to the other components of the PS module, is shown in Fig. 2 (right panel). The MPA processes the signal from PS-p sensors and, using the data received from the readout of the PS-s sensor, implements the p_T discrimination logic discussed in Section 1.

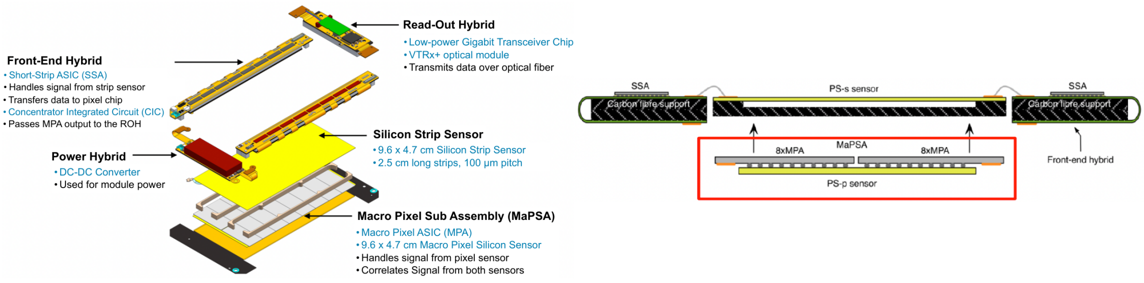

Figure 2: Left: view of the different parts of the PS module, and their functions [3]. Right: cross-section view of the PS module showing the position of the MaPSA (enclosed in the red box) relative to the other components [2].

3. MaPSA test setup and qualification tests

Figure 3 shows the different components of the MaPSA test setup at DESY. A probe card can be used to test one MPA chip at a time. It contains 119 needles, one of which is used to provide high voltage to the sensor, and the other 118 are used to communicate with the same number of pixel columns via wire bonding pads. The MaPSA is placed on a chuck that is mounted on movable stages, which allow repositioning of the MaPSA in x, y, and z coordinates to contact the probe needles with the MPA pads. A user computer communicates (reads/writes data) with the FC7 μTCA card [4], which connects to the probe card via the interface board.

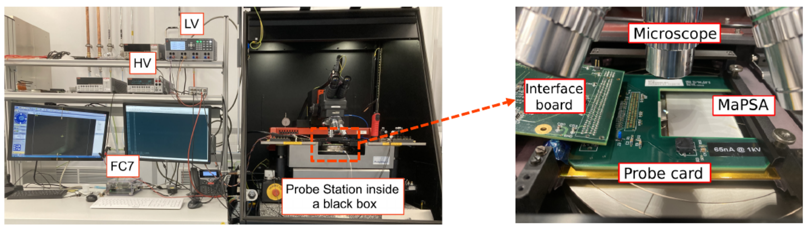

Figure 3: Left: a view of the test setup showing the low and high voltage supplies, the FC7 micro-controller, and the probe station housed in a black box that can be closed during tests to minimize exposure to light. The box is flushed with dry air to create a low relative humidity environment. Right: a close up view of the probe-station, showing the MaPSA, the probe card, the interface board, and the microscope.

The MaPSA qualification procedure consists of a series of tests that are described in the following sub-sections. These tests have been optimized and validated on prototype MaPSAs.

3.1 Sensor IV characteristics

During operation, radiation will change the full depletion voltage of the sensor which requires the reverse bias voltage to be increased in order to maintain the charge collection efficiency. A global test is performed for the entire sensor, which measures the leakage current of the sensor down to a reverse bias voltage of -800 V. A good sensor must show no breakdown, and the leakage current should not exceed 1 μA at a reverse bias voltage of -800 V.

3.2 Pixel alive, mask, and bump bond tests

A signal charge is processed by the MPA front-end (FE) circuit before being read out. Figure 4 (left panel) shows a simplified sketch of the MPA FE circuit. A signal charge can be either be generated by the passage of a charged particle through the sensor, or injected by the discharge of a capacitor in the calibration circuit. The pulse is first passed through an amplifier and shaper to improve the pulse shape, which produces a better signal-to-noise ratio, and also adjusts the pulse rise time and width according to the design requirements. The shaped pulse is then digitized by a comparator circuit that compares the pulse height against a predetermined threshold. The final readout is thus binary – 1 when the pulse height is above the threshold, and 0 otherwise.

In order to check if each MPA pixel channel is alive (can be read out) and is maskable, 100 signal charge pulses are injected into each channel. The pixel alive test checks if 100 pulses are read out from each channel. On the other hand, the pixel mask test checks whether no pulses are read out from a pixel, if its readout is masked. This is important because it may be necessary to mask pixels having a very high noise during operation, which would otherwise produce noise stubs and increase the L1 trigger rate significantly.

The bump bond test checks for a good electrical connection between the sensor and the MPA chips. In order to do so, the pixel noise is measured with a small bias voltage of -2 V. The noise is measured by fitting the s-curve obtained with the CAL-scan method (see Section 3.3). If the pixel has a faulty bump bond, its measured noise will be low as the sensor noise will not appear in the readout. For a given MPA, pixels with noise lower than 5 standard deviations with respect to the mean pixel noise in that MPA, are categorized as bad bump bonds.

3.3 Pixel trimming test

Even for the same amount of injected signal charge, the responses (i.e. whether the pulse amplitude exceeds a certain comparator threshold or not) of different FE readout channels differ because of variations in the manufacturing process of the readout chips. Hence the comparator threshold needs to be adjusted in order to equalize the responses of all the readout channels. This procedure is known as trimming. The trimming process starts with performing a threshold scan (THR-scan) of each pixel in an MPA. A THR-scan involves injecting a certain number (1000 in this case) of signals with a fixed amplitude, varying the comparator threshold, and counting the number of signals recorded at the output for each value of the threshold. The distribution of the number of signal pulses counted at the output as a function of the comparator threshold produces a noise peak and an s-curve. This is illustrated in Fig. 4 (central and right panels). An alternative way to obtain the noise peak and the s-curve is by keeping the comparator threshold constant, but varying the amplitude of the injected signal instead. This is called a calibration scan (CAL-scan). Assuming the noise is Gaussian, the s-curve is then fitted with the error function $f(x) = \frac{1}{2}\,\mathrm{erf}\,(\frac{x-\mu}{\sqrt{2}\sigma})$, where μ and σ are the measured (fitted) pedestal and noise, respectively. The result of a THR-scan on all the pixels in an MPA is presented in Fig. 5 (left panel), which shows how the responses for different pixels vary widely. In order to equalize (trim) the pixel responses, a target pedestal value is chosen, and an offset is applied to the comparator threshold such that the new pedestal is as close as possible to the target. The output of the THR-scan on the trimmed pixels is shown in Fig. 5 (right panel) – the trimmed pixel responses are very similar to one another. The trimming is not perfect (i.e. the trimmed curves do not overlap completely) as the number of bits available for setting the offset in the digital-to-analog converter (DAC) is small, which limits the granularity of the offset.

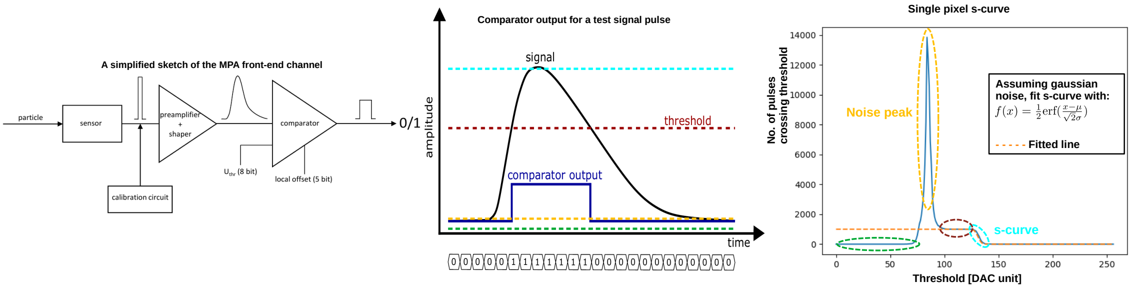

Figure 4: Left: sketch [5] of an MPA FE circuit. Center: sketch [5] of the comparator output (blue solid like) for a signal pulse (black solid line) and threshold (red dashed line). Right: result of a THR-scan for a single pixel. As the comparator threshold is increased from green → yellow → red → cyan as shown in the central panel, the portions of the curve enclosed in ellipses of the corresponding color are obtained.

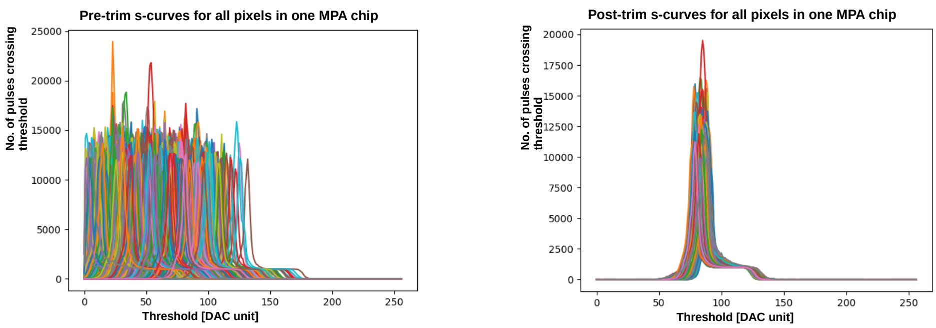

Figure 5: Left (right): result of a THR-scan on all the pixels in an MPA before (after) trimming.

4. Summary

An overview of the MaPSA qualification tests has been presented in this report. The described procedures have been validated on prototype MaPSAs. In order to pass the quality control tests, a MaPSA is required to satisfy the aforementioned requirements on the IV characteristics, have less than 1% faulty (dead or bad bump bond) pixels per MPA, and no unmaskable pixels. The test system is fully functional at DESY, and other MaPSA test sites will be using a very similar setup and procedure. During the production phase, DESY will assemble 1250 PS modules and hence receive the same number of MaPSAs. Since the MaPSAs will be tested by US sites beforehand, 10% of them will retested after shipping, before the PS module assembly.

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