Test Results of the Short Strip ASIC Prototype Module

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Abstract

The Short Strip ASIC (SSA) is one of the four front-end chips designed for the High Luminosity Upgrade of the CMS Outer Tracker. Results from a prototype detector consisting of a sensor and two SSA chips are presented. The obtained performance is consistent with specifications and validate the ASIC design.
1 Introduction

The High Luminosity LHC will operate at an instantaneous luminosity of up to $7.5 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$, which will result in up to 200 proton-proton interactions per bunch crossing [1]. The CMS detector [2] is planned to be upgraded [3] to handle the resulting five-fold increase in radiation and occupancy. Individual CMS sub-detectors will be upgraded or replaced, including the installation of a new Outer Tracker detector. The new Outer Tracker, which will have higher detector granularity, is designed to provide track momentum information to the first level (L1) trigger, so that it can be used to reduce the event rate from 40 MHz to less than 750 kHz [4].

The new tracker will use two types of modules with two silicon sensors forming closely spaced parallel planes. The proposed layout is shown in Figure 1. The modules closer to the beam consist of macro-pixel (100 $\mu$m $\times$ 1460 $\mu$m pitch) and short strip (100 $\mu$m $\times$ 25mm pitch) sensors, each read out by its own microchip. The Short Strip ASIC (SSA) [5] is designed to read out the short strip sensors of the PS module, and can discriminate against two tunable thresholds. Every LHC clock cycle the SSA forms clusters from neighboring hit strips passing the first threshold and passes the centroid position of up to eight such clusters to the Macro Pixel ASIC (MPA) [6]. The MPAs read out the macro-pixel sensor of the PS module and are required to correlate the strip centroids from the SSA against any pixel hits detected to form trigger coincidences from high momentum particles, called stubs (see Figure 2). These stubs are transmitted off-detector and are used to perform fast track reconstruction at 40MHz for the L1 trigger. In addition to the stub stream, the SSA must buffer hits from the strip sensor until it is triggered for readout, upon which cluster data is passed to the MPA for event packing. The second discriminant circuit for each strip is used to detect highly ionizing particles (HIPs).

Figure 1: Sketch of one quarter of the Outer Tracker in $r$-$z$ view. Blue lines represent the silicon sensors of the PS modules, composed of Macro Pixel and Short Strip ASICs. The red lines represent related 2S modules not covered in this paper. The three sub-detectors, named TBPS, TB2S, and TEDD, are indicated.

Figure 2: Diagram of stub formation in the PS module: high momentum particles (left) are less affected by the magnetic field at CMS than a low momentum particle (right), whose trajectory is significantly bent by the field. Simultaneous hits (red) recorded by the MPA and SSA only form a stub if the hits in the SSA are within some fiducial region (blue) of the short-strip sensor, set by the location of the hit in the macro-pixel sensor.

This paper describes a prototype module built in 2019 and the results of its first beam test in January 2020 at the Fermilab Test Beam Facility.
2 Experimental setup

Validation of the PS module, especially timing and resolution studies, are being performed on prototype modules which seek to isolate the performances of individual ASICs. In the case of the SSA, the detector under test (DUT) is referred to as the $2 \times$ SSA module, and consists of a strip sensor connected to two SSA chips. This module was tested in a controlled beam where the known trajectories of incoming protons were exploited to characterize the behavior of the $2 \times$ SSA module.

2.1 SSA

The SSA, built with 65 nm lithography technology, is described in detail in Ref [5]. Each chip can read out 120 channels from a short strip sensor. After amplification and signal shaping in the analog front-end, signals are discriminated with a double threshold binary system. These thresholds can be programmed, with the lower threshold being able to detect hits with energies as low as $1/4$ of the minimum ionizing particle energy (MIP). Signals exceeding either comparator threshold are latched with an edge sensitive circuit able to guarantee no dead cycles for consecutive particle hits, and sampled at 40 MHz. In order to maximize the hit detection efficiency, the sampling clock phase is adjustable with a precision of 200 ps across the full 25 ns period. The hits are transmitted on the two data paths: the stub data path consisting of up to eight hits or clusters of neighboring hits which are passed to the second chip in the PS module for momentum discrimination, and the L1-trigger path, which stores the entire sensor image until it is requested by the trigger system, with latencies up to $12.8 \mu s$.

2.2 $2 \times$ SSA Module

The DUT (shown in Fig. 3) consists of a single, 240 channel p-in-n Float Zone silicon sensor [3] with each channel wire bonded to one of two sapphire interposers which were in turn each bump bonded to an SSA chip. Each sensor strip has a pitch of $100 \mu m$ and length of 23 mm, while the sensor thickness is $240 \mu m$. The sensor is read out by two SSAs, with the center of the sensor corresponding to the boundary between the channels connected to each chip.

![Figure 3: A close-up picture of the DUT. From right to left: The silicon sensor (large gray square), wire bonds connecting it to the interposers, the SSA chips (two small dark rectangles), wire bonds connecting the interposer to the rest of the experimental setup. The interposers are located beneath each SSA, and are not visible in this image.](image)

2.3 Test Beam Parameters

The Fermilab Test Beam Facility at the Fermi National Accelerator Laboratory receives a beam of protons from the Fermilab Main Injector. These protons are delivered in a long spill of 4.2 seconds, once per minute. A picture of the experimental geometry is shown in Fig. 4. The test beam facility is equipped with the silicon tracking telescope at the Fermilab Test Beam Facility [7], a strip and pixel telescope, to precisely measure the path of incoming particles, with an impact resolution of less than $8 \mu m$ at the DUT, which is smaller than the $100 \mu m$ pitch
of the strips on the DUT sensor. The telescope is composed of seven silicon strip planes with pitches of 60 \( \mu m \), and four silicon pixel planes composed of 100 \( \mu m \times 150 \mu m \) pixels and covers an active area of approximately 1.4 cm \( \times \) 1.4 cm at the DUT. The telescope is triggered by a scintillator detector with time resolution of a few hundred picoseconds. During the Jan 2020 test beam the DUT was placed down-stream of the first four strip sensors, followed by the remaining strips planes and finally the pixel planes. This geometry places the DUT closest to the strip planes, which have the highest resolution. The DUT was fixed to a table which can move along or rotate about three axes. The DUT was placed in a 120 GeV proton beam with between 100 and 200 thousand particles per spill and was triggered by and shared a clock with the telescope. Both the DUT and the telescope are read out using the "Off the Shelf" data-acquisition program (OTSDAQ) maintained by Fermilab and processed with the Monticelli software [7]. In particular the online efficiency measurements used to align the DUT with the beam and telescope were measured by Monticelli, and may differ slightly.

![Experimental setup at the test beam.](image)

**Figure 4:** Experimental setup at the test beam. Experimental setup at the test beam. The DUT is in the center of the silicon tracking telescope at the Fermilab Test Beam Facility which is used to measure the tracks of incoming particles with an impact resolution of less than 8 \( \mu m \) at the DUT. During the Jan 2020 test beam the DUT was placed down-stream of the first four strip sensors, followed by the remaining strips planes and finally the pixel planes. The beam travels from left to right along the axis marked “z”.

### 3 Simulations

In Section 4 we compare the performance of the DUT measured at the test beam against a simple model of the sensor whose parameters are fitted to the data to improve the quantitative understanding of the observations. The model assumes an effective depleted region of \( d_{eff} = \min(d_0, d_0 \sqrt{U_h/U_d}) \), with a sensor thickness \( d_0 = 240 \mu m \), a depletion voltage \( U_d = 250 \text{V} \), and an supply voltage \( U_h \). The probabilistic distribution of electron-hole pairs produced by a proton in a silicon sensor is assumed to follow a Landau distribution [8]. The location and width parameters of the Landau distribution are considered free parameters of the model. The horizontal positions of the particles are tracked while they traverse the sensor. The sensors are oriented such that the horizontal positions of the traversing particles are determined.
Table 1: Parameters of the simple model obtained from a fit of the measurements of the efficiencies and cluster sizes for different horizontal angles.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
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<tr>
<td>Landau location</td>
<td>$21,ke^-$</td>
</tr>
<tr>
<td>Landau width</td>
<td>$2,ke^-$</td>
</tr>
<tr>
<td>$\sigma_{\text{diff}}$</td>
<td>$2.8,\mu m$</td>
</tr>
<tr>
<td>$f_x$</td>
<td>$9%$</td>
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an area close to the edges between two strips a diffusion effect is simulated. The fraction of the charge $\Delta Q$ that is lost along a path element $\Delta s$ and observed in the adjacent strip increases as the position approaches the edge. This fraction is described by the integral function of a Gaussian distribution centered at the edge. Its width $\sigma_{\text{diff}}$ describes the size of the diffusion region. The effect of induced signals in strips adjacent to the actual traversed strip (charge sharing) is simulated by sharing a certain fraction of the simulated charge with the adjacent strips. This fraction $f_x$ is another parameter of the model. Finally, after the charges are calculated in all strips they are modulated by a Gaussian distribution to simulate the noise. The noise in the module was measured to be about about 830 electrons. The parameters of the model are fitted to the measurements of the efficiencies and cluster sizes for different horizontal angles (Fig. 9). The four extracted parameters are summarized in Tab. 1.

### 4 Analysis

#### 4.1 Data preparation

Many of the subsequent analyses use clusters, which are formed by contiguous hits in multiple adjacent strips. The position of a cluster is calculated as the average position of the constituent strips. With this definition, cluster positions can be in the middle of two strips. Under default settings, i.e., a threshold of $6200\,e^-$ (1 fC), sensor bias voltage $U_h = 350\,V$, and all rotational angles at zero, 91% of the clusters consist of a single strip and 7% of two strips, with the full distribution of cluster size at three different rotational angles shown in Figure 5.

#### 4.2 Alignment

A first step of the analysis is the calibration of the position and orientation of the DUT with respect to the track trajectories determined by the beam telescope. The goal of this alignment is the calculation of the particle track positions at the surface of the DUT and, consequently, the identification of tracks that do not traverse the sensor of the DUT, or which passed through the DUT without registering a hit. This information is essential for efficiency calculations.

Six parameters are considered in the alignment: the transverse horizontal $x$ and vertical $y$ positions of the origin of the DUT reference frame at the upper left corner of the sensor surface, and its $z$ position parallel to the beam.

In addition, there are three rotation angles of the DUT reference frame: first a rotation angle $\gamma$ around the axis in $z$ direction, second the horizontal rotation angle $\alpha$ around the newly rotated $y$ axis, and finally the vertical rotation angle $\beta$ around the rotated $x$ axis. These parameters are initialized with reasonable values obtained from the experimental settings and then optimized using the tracks from the beam telescope as follows. We calculate the residual between a track and the closest strip, where both are modeled as straight lines. The strips are defined by the pitch and their length by the dimensions of the sensor. The sum of these distances squared is minimized. It is obvious that the information of the strips is not sufficient to constrain all
4.2 Alignment

Figure 5: Distribution of cluster size (number of strips) for three rotational angles. The cluster size increases for higher angles.

The vertical rotation cannot be obtained from the information of the strips. The $y$ position (in the DUT reference frame) can only be constrained if the beam partially crosses the upper or lower edge of the DUT surface. Since the tracks are almost parallel to the beam, the $z$ position becomes arbitrary.

In Fig. 6 the residuals of the track positions at the DUT and the closest cluster are shown as a function of the $y$-position measured with the telescope. Since there is no dependence of $\Delta x$ as a function of the $y$ position, this confirms a successful alignment of the rotation around $z$.

Figure 6: The differences between the track positions and the closest cluster for each event. The means (red) of the distances are flat at zero, confirming a successful alignment.
4.3 Timing resolution

The DUT stores the full hit information for each time window of 25 ns in an internal buffer for up to 12.8 µs. Within this period a trigger decision has to be made to read out and finally store the information of a certain time window. This trigger signal is provided by the beam telescope, which receives the same clock signal as the DUT. The processing and distribution of the trigger signal from the telescope to the DUT takes some time and the correct corresponding entry from the DUT’s internal buffer must be selected. This can be optimized by varying the offset between the trigger arrival and the time of the buffered information. In Fig. 7 the efficiency of observing a telescope track with the DUT is shown as function of the timing offset. For the calculation of the efficiencies, here and elsewhere in this paper, only tracks that point towards the detector surface according to the alignment, are considered. The scan is performed for a threshold of 4800 e⁻, an operating point with high signal efficiency and low noise (as can be seen in Fig. 9). The efficiency has a wide plateau and reaches almost 100%.

The exact shape of the timing scan is more complex, starting from the raw distribution of time periods between a particle incident and the time when the required signal strength is reached. We shift the 25 ns time window of the detector over this raw distribution and count the events. Therefore, the observed shape is the convolution of the raw timing distribution with a uniform distribution of 25 ns length.

In Fig. 8 the ratio of clusters with two or more hits with respect to all clusters is shown. This demonstrates that for the optimum timing the fraction of clusters with more than one hit reaches a maximum. For all studies in this paper the timing was fixed at the indicated working point, although it is slightly sub-optimal. The working point was chosen based on results from online measurements of the efficiency made during data-taking, and which did not properly account for events in which the telescope track was near the edge of the DOT sensor.

![Figure 7: Efficiency as function of the delay of the trigger with respect to a threshold of 4800 e⁻.](image-url)
Figure 8: Fraction of clusters of more than one strip as function of the delay of the trigger.
4.4 Efficiency and cluster size

The efficiency of the module is measured with respect to telescope tracks which point to the module sensor, and counted as a matched hit if they are within $\Delta x = 200 \mu m$ of the telescope track. Extra clusters (which are rare) are ignored. The efficiencies and the cluster sizes are determined as functions of the two threshold values $Q$ and a horizontal rotation angle $\alpha$. The alignment is repeated each time the DUT is rotated so that only telescope tracks pointing towards the sensor in its new position are considered in efficiency calculations. The results are shown in Fig. 9. The efficiency plateaus at 99.7% for thresholds up to $8000 e^-$. For higher thresholds the efficiency drops with a dependence on the particle angle of incidence. This behavior is expected as charge is distributed among several strips at oblique angles, so that the signals on individual strips are reduced and do not reach the threshold. The increased fraction of two strip clusters at higher angles is confirmed by a measurement of cluster sizes as functions of the threshold. The fraction of clusters with two and more hits is always reduced for an increased threshold.

The simple model is fitted to the efficiencies and the cluster sizes as functions of the threshold and $\alpha$ in data. The parameters can be found in Section 3. A decent qualitative description can be reached based just on this simplified model.

![Figure 9](image)

Figure 9: Left: efficiencies as functions of the threshold ($Q$) for various horizontal angles. The measured noise in the module is also shown. Right: fraction of clusters of more than one strip as functions of threshold ($Q$) for various horizontal angles. The measurements (points) are compared to the simulation (solid lines). The statistical uncertainty on the measurements is too small to visualize on this scale.

For each cluster the SSA provides the additional information of whether the signal of at least one constituent hit exceeds a second higher threshold. This information, when combined with data from multiple modules in CMS, can be used to place a lower bound on the energy loss $dE/dx$ of a particle. The selection performance of this second threshold and a comparison to the default threshold when both have been set to the same value is shown in Fig 10. Overall, the second threshold behaves similarly to the main discriminator, though we observe a slightly lower efficiency at a given threshold.

Is there any explanation for this?
4.4 Efficiency and cluster size

Figure 10: Comparison of the efficiencies as functions of the normal selection threshold and the HIP threshold.
4.5 Resolution

The resolution of the sensor is determined for various values of the angle $\alpha$. In Fig. 11 the residual between the cluster position and the corresponding telescope track position are shown separately for one and two strip clusters. The resolutions predicted by the simple model are fitted to the data points, where the telescope resolution is modeled using a Gaussian distribution with a fitted width of $14.7/\cos(\alpha) \mu$m. All other parameters of the simple model are fixed at their values determined in Section 4.4. The obtained predictions provide a good description of the data. In addition to this folded prediction, the unfolded resolutions are also shown, corresponding to the simulated intrinsic resolution of the sensor only. In Fig. 12 the efficiency is shown as a function of the inter-strip position on the DUT sensor, with the position determined using the telescope. Again, we show the convolved model, taking into account the stated telescope resolution of $8 \mu$m, and the simulated efficiency when the effect of the telescope is removed. The efficiency when considering all clusters is flat across the interstrip region and reaches 99.7%.

At $\alpha = 0$ degrees the two strip clusters are concentrated in a narrow region (around $10 \mu$m) half way between strip implants that is determined by diffusion effects. With an increasing angle the chance of traversing two strips becomes geometrically enhanced. Therefore, the fraction of two strip clusters increases, but the resolution degrades due to the increased charge sharing. Conversely, one strip clusters become more restricted to the center of the strips and their resolution is improved.

Figure 11: Residual between the telescope track and cluster positions for different horizontal angles: $0^\circ$ (top left), $3^\circ$ (top right), $8^\circ$ (bottom left) and $13^\circ$ (bottom right). The data, shown with statistical errors, is fitted with the model prediction (dashed lines) convolved with the telescope resolution (solid lines).
Figure 12: Distribution of the interstrip positions of the telescope tracks for different horizontal angles: 0° (top left), 3° (top right), 8° (bottom left) and 13° (bottom right). The data, shown with statistical errors, is fitted with the model prediction (dashed lines) convolved with the telescope resolution (solid lines). The strip implants are located at -50µm and 50µm.
5 Conclusions

The SSA is one of the four front-end chips designed for the High Luminosity Upgrade of the CMS Outer Tracker. The performance of a prototype module consisting of two SSA chips connected to a sensor was tested at the Fermilab Test Beam Facility. The obtained performance is consistent with specifications and validate the ASIC design.

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References


