Beam test performance of a prototype module with Short Strip ASICs for the CMS HL-LHC tracker upgrade

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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. It is a 65-nm CMOS chip, designed to be bump-bonded to a substrate to which the sensor it digitizes is wire-bonded. Together with a Macro-Pixel ASIC (MPA) it will instrument PS-modules, containing a strip and a pixel sensors stacked over each other. The SSA provides both full readout of the strip hit information on the Level-1 trigger accept and, together with MPA, Level-1 trigger primitives (stubs) by correlating clusters in the two sensors. Results from the first prototype detector consisting of a sensor and two SSA chips are presented. The prototype module has been characterized at the Fermilab Test Beam Facility using a 120 GeV proton beam. The obtained performance is consistent with specifications and satisfies CMS requirements.
1 Introduction

The Large Hadron Collider (LHC), will be upgraded to operate at increased instantaneous luminosities of up to $7.5 \times 10^{34}$ cm$^{-2}$/s, which will result in up to 200 proton-proton interactions per bunch crossing, with the goal of accumulating the total integrated luminosity of 3 ab$^{-1}$ [1]. The CMS detector [2] is planned to be upgraded [3] to handle these new data-taking conditions. The new Level-1 trigger system will feature increased latency of 12.5 $\mu$s and be capable of sustaining an accept rate of 750 kHz, compared to the current values of 4 $\mu$s and 100 kHz.

To accommodate these requirements, the entire CMS silicon tracker will need to be entirely replaced. The current tracker [4], composed of a pixel layer and a strip layer will be replaced by two related detectors: the Inner Tracker, occupying the volume within 20 cm from the beam, and the Outer Tracker (OT), shown in Fig. 1. This new tracker will have increased radiation tolerance (able to handle the expected 1 MeV neutron equivalent fluence of $2.3 \times 10^{16}$ n$_{eq}$/cm$^2$), and increased granularity to ensure efficient tracking performance despite the higher particle rates and densities. The OT will use two types of modules (2S and PS), each consisting of two silicon sensors forming closely spaced parallel planes. Correlated clusters from high transverse momentum tracks are identified using on-chip logic and form Level-1 trigger primitives (stubs), as shown in Fig. 2.

The 2S modules, positioned at outer radii where the particle occupancy is lower, are comprised of two strip sensors digitized by a CBC3 chip and have been extensively described [5, 6]. The PS modules are situated closer to the beam and consist of macro-pixel (100 $\mu$m pitch $\times$ 1460 $\mu$m length) and short strip (100 $\mu$m pitch $\times$ 25 mm length) sensors. The Macro Pixel ASICs (MPA) [7] are bump-bonded to the former, while the latter is wireboned to a hybrid and is read out by the Short Strip ASIC (SSA) [8, 9] bump-bonded to the same hybrid. The Concatenator Integrated Circuit (CIC) [10] distributes clock, trigger and control signals to the eight SSAs and eight MPAs on each side of the module, and is responsible for aggregating their returned data. A diagram of the PS module is shown in Fig. 3. The SSA is the only OT chip that is capable of flagging hits with large ionization (HIP) by discriminating the hit amplitude against a programmable “HIP threshold”. SSA also performs strip hit clustering and transmits the clusters to MPA to be used for stub formation.

This paper describes the first prototype detector module consisting of the sensor with the same strip configuration as in the final detector and two SSA chips. The module was built in 2019 and tested in January 2020 at the Fermilab Test Beam Facility, with the primary goal of verifying the chip front-end performance.

The paper will first describe the SSA chip, two-SSA module under test and the experimental
Figure 2: Diagram of stub formation in the PS module: high momentum particles (left) are less affected by the 3.8 T magnetic field created by the CMS solenoid 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, seeded by the location of the hit in the macro-pixel sensor. Conceptually, the stub formation in the 2S modules is similar to that for the PS shown here.

Figure 3: Diagram of the PS module, showing (starting from the topmost layer): the strip sensor (yellow), MPAs (grey) and pixel sensors in the central part of the module. The SSAs are wirebonded to the edge of the strip sensor.
setup at the test beam facility. A simulation of the expected performance of the module is described, as is the procedure by which this model was tuned. Finally, the collected data at different incident angles and its compatibility with the simulation is reported for measurements of the module timing, hit reconstruction efficiency, cluster size and resolution.

2 The Short Strip ASIC

The SSA, built with 65 nm CMOS technology, is described in detail in Ref. [8]. Each SSA 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: one for the L1 hit data (standard threshold) and for the HIP flagging (HIP threshold). These thresholds (Q) can be programmed, with the nominal thresholds set to detect hits with energies of 1/4 of the minimum ionizing particle (MIP) energy (a signal of approximately 4500 e− for the strip sensor) for the standard threshold and 1.4 MIPs (approximately 25k e−) for the HIP threshold. Both signals are digitized with an edge sensitive circuit sampled at 40 MHz. In order to maximize the hit detection efficiency, the sampling clock phase is adjustable in steps of 200 ps across the full 25 ns bunch crossing period. The hits are transmitted via two data paths: the stub data path which carries up to eight hits or clusters of neighboring hits which are passed to the MPA 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 µs. All results in this paper are based on the latter. A data-flow diagram for the SSA and MPA combination, as intended for use in the full PS module is shown in Figure 4.

![Figure 4: Data-flow diagram for the PS module, showing both the SSA and MPA sides.](image)

3 Experimental setup

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

3.1 2×SSA Module

The DUT (shown in Fig. 5) consists of a single, 240 channel p-in-n Float Zone silicon sensor [11] 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 µm and length of 23 mm, while the sensor thickness is 240 µm. The sensor is read out by two SSAs, with the boundary between the 120 channels connected to each chip located at the center of the sensor. To ensure full depletion of the silicon, the sensor was biased to $-350\,\text{V}$ for all results presented here. The standard thresholds were set to 6200 e$^-$ (unless otherwise indicated). Each chip’s stub data lines, intended to pass cluster locations to the MPA in the PS module, are instead connected to the other chip. This feature was used to verify the functionality of these data lines, but is not used in any aspect of the data processing from this beam test.

Figure 5: (Top) 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 printed circuit board. The interposers are located beneath each SSA, and are not visible in this image. (Bottom) A diagram of the 2xSSA Module. The SSAs are bump bonded (PbSn) to the sapphire interposers through which are in turn bump bonded to the strip sensor channels and the printed circuit board (PCB) in a similar configuration to how the eventual PS modules will be constructed. Power, communication and data lines are passed to the SSAs from the PCB through the wire bonds and bump bonds. High voltage to bias the sensor is provided by the PCB.

Due to process variations in the lithography of the ASICs, individual channel front-ends may respond differently for a nominal threshold setting. To account for this, every SSA channel’s standard discriminator threshold is individually adjustable with an additional offset. To ensure an even response across all channels, these are tuned on a known signal: a calibration pulse from the discharge of an on-board 52 fF capacitor. The DC level of this calibration line is controllable, and can be tuned against an external reference to ensure a known charge is injected.

3.2 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
3.3 Data Acquisition

The data acquisition system is built around the FC7 card [13], a specialized µTCA compatible Advanced Mezzanine Card (AMC) equipped with a Kinetex 7 FPGA. The FC7 communicates with both chips through an FPGA Mezzanine Card (FMC). Commands are sent to the SSAs via I2C protocol and through a dedicated fast command line which sends the trigger accept signals. The chips send signals to the FC7 through a total of seventeen SLVS lines. Fifteen of these lines are for the cluster centroids which are sent at each 40 MHz clock cycle (note that the eighth stub line of one SSA is not connected on the 2xSSA module). The remaining two lines are for the L1-trigger data of each chip, and only send data when the DUT is triggered. The triggers from the telescope and the shared clock are input to the FC7 with a second FMC. The FPGA firmware implementation is specific to the 2xSSA module, and is controlled by the Phase 2 Acquisition and Control Framework (Ph2 ACF) developed for the Outer Tracker Upgrade program.

Both the DUT and the telescope are read out using the “Off the Shelf” data-acquisition program (OTSDAQ) [14] maintained by Fermilab and processed with the Monicelli software package for track reconstruction and alignment [12]. The online efficiency measurements used to align the DUT with the beam and telescope were measured by Monicelli, and may differ slightly from the efficiency measured offline, due to the sensitivity of the efficiency measurement to the exact position of the sensor boundaries.

4 Simulations

In Section 5 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 goal of the model is to predict the amount of charge collected in each strip of the sensor, for different interstrip positions (x) and incident angles (θ) of the incoming protons. The parameters of the model are fit to the measurements of the efficiencies and cluster sizes for different horizontal angles (Fig. 11). The model assumes an effective depleted region of \( d_{\text{eff}} = \min(d_0, d_0 \sqrt{U_h/U_d}) \), with a sensor thickness \( d_0 = 240 \mu m \), a depletion voltage \( U_d = 250 V \), and an supply voltage \( U_h \). The probabilistic distribution of electron-hole pairs produced by a proton entering the silicon sensor is assumed to follow a Landau distri-
Figure 6: Experimental setup at the Fermilab Test Beam Facility. The DUT was placed on a rotating table at the center of the silicon tracking telescope (only five silicon planes pictured). The beam travels from left to right along the axis marked $z$.

The most probable value ($\mu$) and width ($\sigma$) parameters of the distribution are considered free parameters of the model. The charge is increased to $\mu \times 1/\cos \theta$ to account for the incident angle. If the proton crosses multiple strips, the charge is divided between the two strips proportional to the distance traversed in each strip. Two additional effects are taken into account: diffusion of charge from one strip to another, and capacitive coupling between the strips. In an area close to the edges between two strips a charges may diffuse across the strip boundaries. 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 (the Erf). Its width $\sigma_{\text{diff}}$ describes the size of the diffusion region, and is a free parameter of the model. The effect of induced signals in strips adjacent to the actual traversed strip due to the capacitive coupling between strips (charge sharing) is simulated by adding a certain fraction of the simulated charge in the adjacent strips (and subtracting it from the adjacent strip). 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 combined noise from the SSAs and sensor. The noise was measured after the DUT was installed at the Test Beam Facility, prior to receiving beam, and is found to be about 830 electrons. Taking all these components, the total charge collected by a strip $A$, when the sensor is traversed by the proton along a path $S$ which also crosses strip $B$ is given by:

$$C_{\text{tot},A} \approx (1 - f_x) \int_S \frac{\{L\}}{S} \text{Erf} \left( \frac{x - x_e}{\sqrt{2\sigma_{\text{diff}}}} \right) ds + f_x \int_S \frac{\{L\}}{S} \text{Erf} \left( \frac{x_e - x}{\sqrt{2\sigma_{\text{diff}}}} \right) ds + \{N\}$$

where $\{L\}$ is sampled from the Landau distribution with most probable value ($\mu$) and width ($\sigma$), $x_e$ is the position of the boundary between strips $A$ and $B$. The noise $\{N\}$ is sampled from a gaussian with width 830 electrons. Additional terms could be added for other adjacent strips, but these effects are negligible if the proton does not traverse them.

The four extracted parameters are summarized in Tab. 1. Notably, the post-fit value of $\mu$ is...
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>
</thead>
<tbody>
<tr>
<td>Landau $\mu$</td>
<td>$20.6 \pm 0.2$ ke$^-$</td>
</tr>
<tr>
<td>Landau $\sigma$</td>
<td>$1.8 \pm 0.1$ ke$^-$</td>
</tr>
<tr>
<td>$\sigma_{\text{diff}}$</td>
<td>$2.8 \pm 0.5$ $\mu$m</td>
</tr>
<tr>
<td>$f_x$</td>
<td>$9.3 \pm 0.2%$</td>
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20,600 electrons, close to the expected value of 19,000 for a 120 GeV electron in 240 $\mu$m of silicon.

5 Analysis

5.1 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. The studies presented in this paper use clusters reconstructed after data-taking from the L1 hit outputs of the DUT. This allows the analysis to consider the number of strips in each cluster, rather than just the positions output by the SSAs. 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), a 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. The distributions of number of clusters $N_{cl}$ as function of the cluster size for three different rotational angles $\alpha$ are shown in Fig. 7, and we see that the average cluster size increases for higher angles.

![Figure 7: Number of clusters $N_{cl}$ as function of the cluster size (number of strips) for three horizontal rotational angles $\alpha$. Each distribution is normalized to unity.](image)

5.2 Alignment

The 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.

Six parameters are considered in the alignment. There are 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 seen in Fig. 6: a rotation angle $\gamma$ around the axis in $z$ direction; the horizontal rotation angle $\alpha$ around the $y$ axis; and finally the vertical rotation angle $\beta$ around the rotated $x$ axis (all angles are shown in Fig. 6). These parameters are initialized with reasonable values obtained from the experimental settings and then determined precisely using the tracks from the beam telescope as follows. We calculate the residual between a track (modeled as a straight line) and the closest cluster centroid. The strips are defined by the pitch and their length by the dimensions of the sensor. The sum of these distances squared is minimized for each configuration of the DUT. It is obvious that the information of the strips is not sufficient to constrain all parameters necessary for an absolute three-dimensional positioning of the DUT. The vertical rotation $\beta$ 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. As the results presented below have no dependence on these parameters, they can safely be ignored.

In Fig. 8 the residuals of the track positions at the DUT and the cluster centroid ($\Delta x$) 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 angle $\gamma$ around $z$.

Figure 8: Distribution of the residuals ($\Delta x$) between track position and closest cluster centroid as a function of $y$-position measured by the telescope, for each event. The residual distribution has no dependence on the vertical position $y$, confirming a successful alignment. The average value of the residuals as a function of $y$-position is shown in red.
5.3 Timing efficiency

The SSA 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 should be made if the full hit data is to be read out and stored. This trigger signal is provided by the beam telescope, which receives the same clock signal as the DUT. Since the processing and distribution of the trigger signal from the telescope to the DUT takes some time the correct corresponding entry from the DUT’s internal buffer must be selected. This can be achieved by adjusting either the trigger arrival time or the pointer to the pipeline location containing the buffered hits. In Fig. 9 the efficiency of observing a reconstructed track in coincidence with a cluster in 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 standard threshold of 4800 e−, an operating point with high signal efficiency and low noise (as can be seen in Fig. 11). The efficiency has a wide plateau and reaches 99.75%.

In Fig. 10 the ratio of the number of clusters with two or more hits \(N^\geq 1_{cl}\) 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. Such clusters become increasingly likely as the incident angle of the beam increases and charge deposited by the protons is more likely to be recovered across multiple strips.

For all the studies in this paper the timing was fixed at the indicated working point, although it has slightly sub-optimal efficiency. The working point was chosen based on results from online measurements of the efficiency made during data-taking. This online calculation, which uses a less precise geometric alignment of the DUT, did not reject tracks just outside the actual sensor boundary from being considered when computing the efficiency.

![Efficiency as function of the delay of the trigger for a standard threshold of 4800 e⁻. The chosen working point is indicated by the dashed vertical line.](image-url)
Figure 10: Fraction of clusters with more than one strip $N_{cl}^{-1} / N_{cl}$ as function of the delay of the trigger. The chosen working point is indicated by the dashed vertical line.
5.4 Efficiency and cluster size

The efficiency of the module is measured with respect to telescope tracks which point to the sensor, and counted as a matched hit if they are within $\Delta x = 200 \mu m$ of the telescope track. Clusters not associated with a track are discarded. The efficiencies and the cluster sizes are determined as functions of the standard threshold value $Q$, and the 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. 11. The efficiency plateaus at 99.7% for standard 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 a function of the threshold. The fraction of clusters with two or more hits ($N_{cl}^2/N_{cl}$) is always reduced for an increased threshold.

The simple model described in Section 4 is fitted to the measured efficiencies and the cluster sizes as functions of the threshold and $\alpha$. The parameters can be found in Tab. 1. A decent qualitative description can be reached based on this simplified model.

For each cluster the SSA provides additional information when the signal of at least one constituent hit exceeds a second higher HIP 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 standard threshold is shown in Fig. 12. Overall, the HIP threshold behaves similarly to the main discriminator, though we observe a slightly lower efficiency at a given value of $Q$. 

![Figure 11: Left: efficiencies as functions of the threshold $Q$ for various horizontal angles $\alpha$. The measured noise in the module is also shown. Right: fraction of clusters with more than one strip $N_{cl}^2/N_{cl}$ as a function of $Q$ for various horizontal angles $\alpha$. The measurements (points) are compared to the simulation (solid lines).](image-url)

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Figure 12: Comparison of the efficiencies as functions of the standard threshold (filled dots) and the HIP threshold (open crosses).
5.5 Resolution

The resolution of the sensor is determined for various values of the angle $\alpha$. In Fig. 13 the residuals 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 simultaneously across all angles, where the telescope resolution is modeled using a Gaussian distribution with a fitted width of 14.7 $\mu$m. This value corresponds to the resolution of the track position on the DUT when the sensor is parallel to the telescope planes ($\alpha = 0^\circ$). When the DUT is rotated the effective telescope resolution is modified by a factor of $1 / \cos \alpha$. All other parameters of the simple model are fixed at their values determined in Section 5.4. 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. 14 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 14.7 $\mu$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 $\alpha = 0^\circ$ the two-strip clusters are concentrated in a narrow region (around 10 $\mu$m) between strip implant centers, mainly 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 are constrained to the center of the strips and their resolution is improved.

Figure 13: Residual between the telescope track and cluster positions for different angles $\alpha$: $0^\circ$ (top left), $3^\circ$ (top right), $8^\circ$ (bottom left) and $13^\circ$ (bottom right). The data, shown with statistical errors, are fitted with the model prediction (dashed lines) convolved with the telescope resolution (solid lines).
Figure 14: Distribution of the interstrip positions of the telescope tracks 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, are fitted with the model prediction (dashed lines) convolved with the telescope resolution (solid lines). The border between two strips is at 0 $\mu$m, and the strip implants are centered at -50 $\mu$m and 50 $\mu$m.
6 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 using 120 GeV protons. This 2xSSA module was constructed to closely approximate the sensor-ASIC configuration used in the full PS-module, and these measurements constitute the first published results of the SSA performance. The performance of the module was tested at incident beam angles between 0° and 18° to emulate track bending in a magnetic field. The module is shown to be fully efficient, at all angles, for the nominal 1 particle detection thresholds, and the functionality of a second highly ionizing particle detecting threshold is confirmed. The results agree closely with simulation of the protons interacting with the silicon sensor, including at the boundaries between sensor channels where clusters consisting of multiple strips are more likely to occur. The compatibility of the data and simulation indicate that the performance is consistent with expectations and validates the ASIC front-end design, module construction and Ph2 ACF DAQ system.

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References


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