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Beam Test Results of Silicon Sensor Module Prototypes for the Phase-2 Upgrade of the CMS Outer Tracker

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Abstract

The start of the High-Luminosity LHC (HL-LHC) in 2027 requires upgrades to the Compact Muon Solenoid (CMS) Experiment. In the scope of the upgrade program the complete silicon tracking detector will be replaced. The new CMS Tracker will be equipped with silicon pixel detectors in the inner layers closest to the interaction point and silicon strip detectors in the outer layers. The new CMS Outer Tracker will consist of two different kinds of detector modules called PS and 2S modules. Each module will be made of two parallel silicon sensors (a macro-pixel sensor and a strip sensor for the PS modules and two strip sensors for the 2S modules). Combining the hit information of both sensor layers it is possible to estimate the transverse momentum of particles in the magnetic field of 3.8 T at the full bunch-crossing rate of 40 MHz directly on the module. This information will be used as an input for the first trigger stage of CMS. It is necessary to validate the Outer Tracker module functionality before installing the modules in the CMS experiment. Besides laboratory-based tests several 2S module prototypes have been studied at test beam facilities at CERN, DESY and FNAL. This article concentrates on the beam tests at DESY during which the functionality of the module concept was investigated using the full final readout chain for the first time. Additionally the performance of a 2S module assembled with irradiated sensors was studied. By choosing an irradiation fluence expected for 2S modules at the end of HL-LHC operation, it was possible to investigate the particle detection efficiency and study the trigger capabilities of the module at the beginning and end of runtime of the CMS experiment.

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Beam Test Results of Silicon Sensor Module Prototypes for the Phase-2 Upgrade of the CMS Outer Tracker

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It is necessary to validate the Outer Tracker module functionality before installing the modules in the CMS experiment. Besides laboratory-based tests several 2S module prototypes have been studied at test beam facilities at CERN, DESY and FNAL. This article concentrates on the beam tests at DESY during which the functionality of the module concept was investigated using the full final readout chain for the first time. Additionally the performance of a 2S module assembled with irradiated sensors was studied. By choosing an irradiation fluence expected for 2S modules at the end of HL-LHC operation, it was possible to investigate the particle detection efficiency and study the trigger capabilities of the module at the beginning and end of the runtime of the CMS experiment.

Keywords: Particle tracking detectors (Solid-state detectors), Radiation-hard detectors

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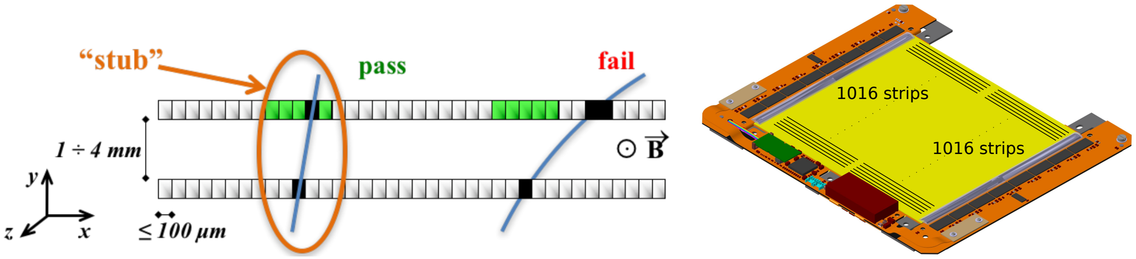
Contents

1 Introduction

The Large Hadron Collider (LHC) at CERN is scheduled to enter the first physics runs during the High-Luminosity LHC phase in 2027. In this phase the accelerator will operate at instantaneous luminosities between $5 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ and $7 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. In order to allow efficient operation the accelerator and its experiments have to undergo several upgrades to cope with the increased particle collision rates.

The Compact Muon Solenoid (CMS) experiment is one of the two general-purpose detectors at the LHC storage ring. The CMS Silicon Tracker will be completely replaced during Long Shutdown 3 of the LHC between 2025 and 2027 in the Phase-2 Upgrade [1]. By installing detector modules that consist of two closely spaced parallel silicon sensor layers in the outer part of the CMS Tracker, it is possible to discriminate between tracks with different transverse momenta p_T on module level at the LHC bunch crossing rate of 40 MHz. This information will be used as an input for the CMS trigger system. Fig. 1(a) illustrates the working principle of the p_T discrimination. By reading out the signal of both sensors using a common set of chips it is possible to determine the distance between the cluster centers in the two sensor layers. Due to the CMS magnetic field of 3.8 T the trajectories of charged particles are bent depending on the particles' transverse momenta p_T. The correlation logic is implemented in such a way that the sensor nearer to the interaction point acts as seed layer. For each cluster in the seed layer a correlation window is opened in the second sensor. In case a cluster combination in both sensors fulfills the correlation criterion a so-called stub is formed and the information about stub position and bend is sent out by the modules to the CMS trigger system. Thus, it is possible to reject low p_T particles in the data stream for the trigger decision.

Depending on the sensor combinations, the modules are called PS modules (combination of a macro-pixel sensor and a strip sensor) and 2S modules (two strip sensors per module) [2]. A 3D rendering of a 2S module is shown in Fig. 1(b). The silicon strip sensors are marked in yellow. Each



(a) (b)

Figure 1: (a): A sketch of the stub logic functionality is shown. Trajectories of charged particles with low transverse momentum can be rejected by comparing the cluster information of both module sensors and allowing only cluster combinations which are inside a configurable correlation window [1]. (b): A 3D rendering of a 2S module. The silicon strip sensors are marked in yellow, the two front-end hybrids housing the readout chips and the service hybrid for module powering and data transmission are coloured orange. The two rows of 1016 strips each are sketched in black on the top sensor.

sensor consists of 2032 5 cm long strips arranged in two rows. The pitch between the strips in each row is 90 µm. The sensors are mounted back-to-back with a distance of 1.8 mm or 4 mm by gluing them onto isolated spacers made of aluminium / carbon fibre composite. Each row of strips is read out by eight CMS Binary Chips (CBCs) [3] located on the two front-end hybrids glued next to the sensors. The electrical connection between strips and readout channels is realised by wire-bonds. The CBC data is serialised, converted to an optical signal and sent out to the off-detector electronics. The module is powered by a DC-DC converter mounted together with the chips for optical data transmission on the service hybrid [4].

2 Beam Test Setup

In 2020, two beam tests were performed with 2S module prototypes at the DESY Test Beam Facility [5]. Fig. 2 depicts the setup. An electron beam with adjustable energy of up to 6.3 GeV is traversing an EUDET-type beam telescope consisting of six MIMOSA26 active pixel devices to allow offline track reconstruction [6]. All measurements presented in this paper were performed with a beam energy of 4.8 GeV or 5 GeV. The 2S module prototypes were inserted in the telescope center as device under test (DUT) dividing the six telescope planes in three upstream and three downstream plane triplets. The DUT box was mounted on a rotation stage. As the MIMOSA26 devices do not provide a 25 ns timing granularity matching the DUT an additional detector was installed in the downstream telescope triplet to provide a timing reference. For data taking the EUDAQ framework was used [7]. The track reconstruction was performed with the EUTelescope framework [8].

The results presented in this article are based on measurements performed with the first 2S module prototypes that were read out optically via the service hybrid. Besides data from unirradiated modules, measurements with a module built with irradiated sensors are shown. The sensors were irradiated to a fluence of $4.6 \times 10^{14}\,\mathrm{n_{eq}/cm^2}$ with 23 MeV protons prior to the module assembly.

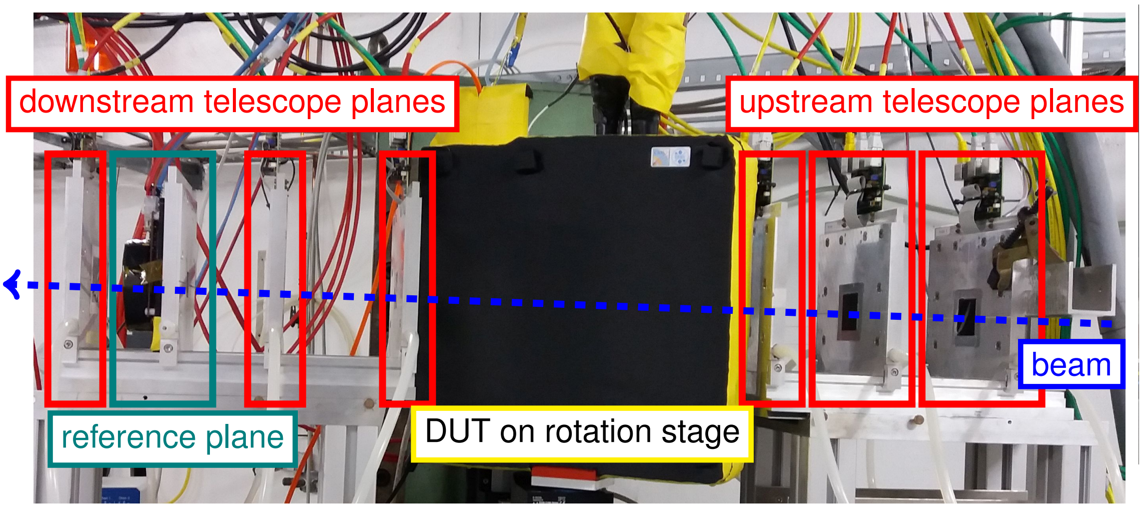


Figure 2: Photo of the beam test setup: the electron beam is detected by three upstream and three downstream telescope planes marked in red. The 2S module prototypes are mounted on a rotation stage in the middle of the telescope as device under test (DUT). An additional detector is mounted in the downstream telescope triplet to provide a timing reference.

This fluence corresponds to 125% of the maximum fluence expected for 2S modules after ten years of HL-LHC operation with an integrated luminosity of 3000 fb^{-1} delivered to the CMS experiment. Sensor properties like signal generation and leakage current level are changing after irradiation due to the introduced radiation damage to the sensor. By annealing these sensor properties can be further influenced. In order to study the effect of different annealing states on the module performance, the top sensor of the irradiated module was annealed to an equivalent annealing time of ten days at room temperature while the bottom sensor was annealed to an equivalent time of 200 days at room temperature. The measurements with the unirradiated modules were performed at a sensor temperature of about +23°C. The module with irradiated sensors was operated at a sensor temperature of about -17°C during the measurements.

3 Data Analysis Definitions

For the analysis the following definitions are used.

The **noise occupancy** is the probability to detect a hit per readout channel and event when the electron beam is turned off.

For the track reconstruction the cluster positions on all six telescope planes are used. Only track candidates that produce clusters on each plane are accepted as reconstructed tracks. On a track basis, the intercept of the reconstructed tracks with the reference plane and the two 2S sensor planes are interpolated. By comparing the interpolated coordinates with the hits registered on the detectors, it is possible to define a detection efficiency. The number of tracks with coinciding predicted track coordinates and detected clusters on the reference plane is given by $n_{\text{ref tracks}}$. Regarding the track interpolations to the seed and correlation sensor in the 2S module prototypes the number of tracks fulfilling both Equations (3.1a) and (3.1b) is defined as $n_{\text{matched tracks}}$.

$$\Delta x(\text{track on seed, stub position}) \leq 200\,\mu\text{m} \tag{3.1a}$$
$$\Delta x(\text{track on correlation, stub position + stub bend}) \leq 200\,\mu\text{m} \tag{3.1b}$$

Thus, the **stub efficiency** is defined as

$$\epsilon_{\text{stub}} = \frac{n_{\text{matched tracks}}}{n_{\text{ref tracks}}} . \tag{3.2}$$

4 Results

4.1 Signal Measurement

The CBC provides a binary readout of the sensor signal. Thus, the integrated signal spectrum was measured by applying different chip thresholds set in the internal ADC unit V_{CTH}. The ADC unit was translated to electron equivalent threshold values using the conversion factor $1\,\text{V}_{\text{CTH}} = 156\,\text{e}^-$ [9]. Fig. 3 compares the stub efficiencies and noise occupancies as a function of chip threshold for the unirradiated module and the module with irradiated sensors. Before irradiation the module was biased at the nominal operation voltage of 300 V. The stub efficiency stayed constant at a plateau with more than 99% stub efficiency up to thresholds of $10\,000\,\text{e}^-$ before decreasing. The irradiated sensors were operated at a nominal bias voltage of 600 V. For a chip threshold of $5000\,\text{e}^-$ the stub efficiency reached the same level as before irradiation. However, due to the radiation damage reducing the signal, the efficiency decreased at much lower threshold values compared to the situation before irradiation. By increasing the bias voltage to 800 V a slight increase in the stub efficiency could be achieved.

The noise occupancy before and after irradiation was consistent and lower than 10^{-5} for chip thresholds larger than $4500\,\text{e}^-$. A maximum channel occupancy of about one percent is expected for the operation of 2S modules during the full HL-LHC phase [1]. Thus, the module noise occupancy is three orders of magnitude below the expected channel occupancy which allows efficient data taking with the modules.

4.2 Performance of Transverse Momentum Discrimination

To probe the performance of the stub logic the particle incidence angle onto the modules was varied by rotating the 2S module prototypes using the rotation stage in the center of the telescope. The resulting stub efficiency distribution before and after irradiation as a function of the module rotation angle ϑ is shown in Fig. 4. For modules orientated parallel to the beam pipe axis the rotation angle can be directly transformed into an emulated transverse momentum by using the magnetic field of 3.8 T in the CMS experiment and the radial distance R of a specific module to the interaction point

$$p_T\,[\text{GeV}] \approx \frac{0.57 \cdot R[\text{m}]}{\sin\vartheta} . \tag{4.1}$$

Fig. 4 is evaluated for the 2S module closest to the interaction point at $R = 71.5$ cm.

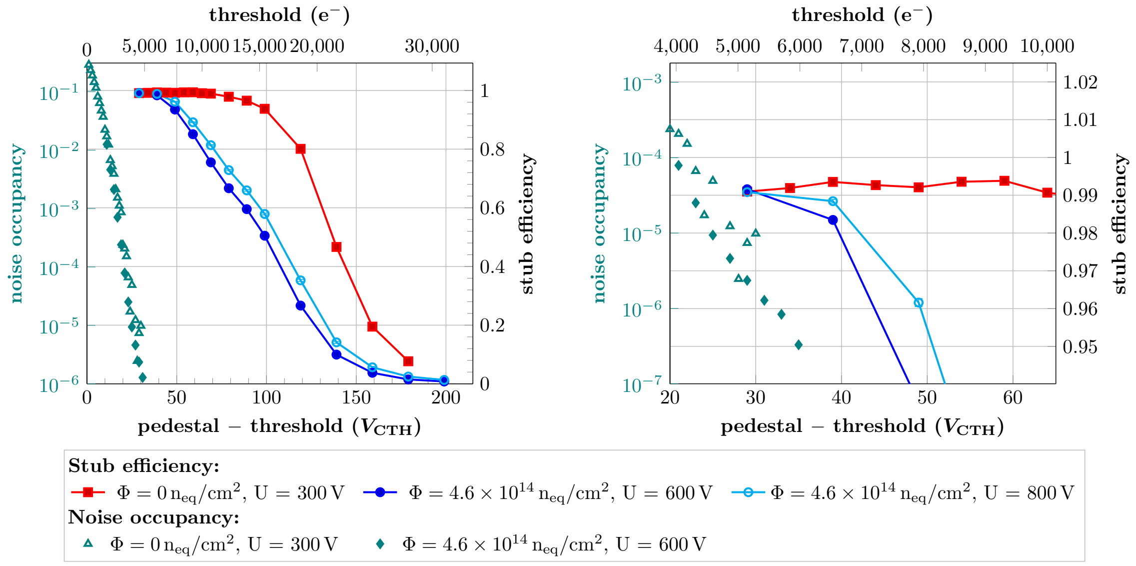


Figure 3: The noise occupancy (left scale) and stub efficiency (right scale) as a function of the readout chip threshold for unirradiated sensors (red) and sensors irradiated to $4.6 \times 10^{14}\,\mathrm{n_{eq}/cm^2}$ (blue). A magnified version of the left figure can be seen on the right.

For small module rotation angles, corresponding to large p_T values, the cluster offsets in the two 2S sensors were within the correlation window and, thus, the stub efficiency was at a plateau at high efficiency. With increasing rotation angle the cluster offset increased and reached the border of the programmed correlation window. This lead to a drop in the stub efficiency to zero. The unirradiated module has been tested with a correlation window size of ±5 strips while the module with irradiated sensors was measured with a correlation window size of ±4.5 strips. As expected a larger window size resulted in a lower cut on the transverse momentum.

By geometrical considerations, the position of the stub efficiency drop can be calculated, taking into account the measured mid point sensor distance of the 2S module prototypes of $d \approx 1.67$ mm. The resulting values are in accordance with the parameters extracted from an error function fit performed with the measurement data.

5 Conclusions

The Tracker Group of the CMS collaboration has performed several beam tests with the first 2S module prototypes providing optical readout at the DESY beam test facility. Besides investigating the module performance before irradiation, a module assembled with sensors irradiated with 23 MeV protons to a fluence of $4.6 \times 10^{14}\,\mathrm{n_{eq}/cm^2}$ was tested. Both before and after irradiation the modules show a stub efficiency of more than 99% at reasonably low readout chip thresholds of around 5000 e^- together with a noise occupancy below 10^{-5}. Such performance will allow efficient data taking during the HL-LHC operation.

Additionally, the stub efficiency was measured as a function of the module rotation angle with respect to the beam incidence direction to emulate tracks with different transverse momenta. Within

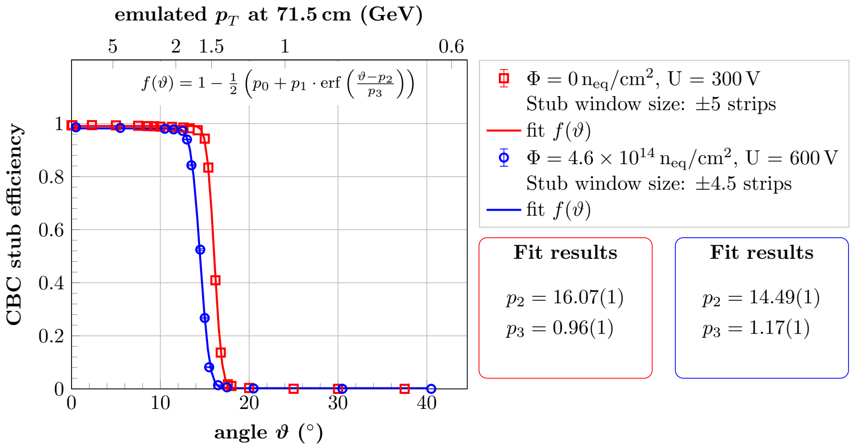


Figure 4: The stub efficiency as a function of the module rotation angle with respect to the beam incidence (lower scale) and the emulated p_T (upper scale) for unirradiated sensors (red) and sensors irradiated to $4.6 \times 10^{14}\,\mathrm{n_{eq}/cm^2}$ (blue). A readout chip threshold of $\approx 6000\,\mathrm{e^-}$ was chosen for both measurements.

the programmed stub correlation window the stub efficiency was at the expected level of more than 99%. Consistent with the geometrical expectation, the stub efficiency drops to zero according to the correlation window size. Larger window sizes correspond to lower transverse momentum cuts.

Based on the results presented in this article, the functionality of 2S modules can be considered proven for unirradiated as well as proton irradiated sensors up to a fluence of $4.6 \times 10^{14}\,\mathrm{n_{eq}/cm^2}$.

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