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Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

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Performance studies for the new CMS outer tracker module concept at HL-LHC based on measurements of charge collection properties in irradiated silicon sensors

Andreas Nuernberg on behalf of the CMS Tracker Collaboration

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Performance studies for the new CMS Outer Tracker module concept at HL-LHC based on measurements of charge collection properties in irradiated silicon sensors

Andreas Nürnberg[☆]

Institut für Experimentelle Kernphysik (IEKP), Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany

Abstract

In order to increase the discovery potential of the experiments at the Large Hadron Collider, the high-luminosity phase of the LHC (HL-LHC) is expected to deliver a total of 3000 fb^{-1} integrated luminosity. The instantaneous luminosity will be increased by a factor of 5 compared to the LHC design luminosity. This results in an intensified track density and radiation level especially in the tracking systems, requiring new radiation hard silicon sensors for the CMS Outer Tracker. To cope with the increased track density and trigger rates, a new module concept based on the coincidence of hits in two closely stacked sensors is pursued for the new tracker, allowing the use of tracking and transverse momentum information already at the first trigger level. The performance of the new trigger module concept has been studied using a parametrization of the charge drift in the electric and magnetic field in the sensor. From that, the phase-space of efficient operation for this module concept and the binary readout in terms of collected charge and noise has been explored.

1. Introduction

The improvement of the LHC machine after 2023 is a challenge for the detectors, especially for the tracking devices close to the interaction point [1]. In the high luminosity phase, the instantaneous luminosity will be increased by a factor of five with respect to the LHC design, from $1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ to $5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. This results in a pile-up of up to 200 collisions per bunch crossing (every 25 ns) with thousands of charged particle tracks in each event. The Outer Tracker of the CMS detector [2] cannot cope with this harsh environment. For that, a completely new tracking detector has to be built.

The high track density implies several requirements the new detector has to meet. Most importantly, the new detector has to contribute to the first trigger stage of CMS to reduce the overall trigger rate. For that, a new module concept with two stacked sensors close to each other is pursued allowing a simple discrimination of the transverse momentum of the particle in the strong magnetic field.

The integrated luminosity is planned to be increased by a factor of six with respect to the LHC design, from 500 fb^{-1} to 3000 fb^{-1} over the foreseen run-time of 10 years. This sets the need for more radiation hard silicon sensors and the cooling of the sensor material to -20°C to mitigate the impact of radiation damage. Still, the properties of radiation hard sensors are altered by the radiation damage and the consequences on module operation are discussed here.

Figure 1: Trigger module concept using two stacked sensors to estimate the transverse momentum of the particle.

2. Trigger module concept

In order to keep the overall trigger rate at an acceptable level, information by the tracker has to be included in the trigger logic. Due to the limited readout bandwidth, it is not possible to send out information about every particle hit in the tracker at the full bunch crossing rate of 40 MHz. The first stage of data reduction has to be directly in the detector. Exploiting the strong magnetic field in the tracker volume, the front-end chips perform a simple p_T -discrimination by coincidence of hits in two closely stacked sensors, as illustrated in figure 1. In the inner part of the detector, for radii below 60 cm a combination of a strip and a macro-pixel sensor (PS-module) will be used, in the outer part at $R > 60 \text{ cm}$, two strip sensors (2S-module) will be combined. Details on the module geometry are given by table 1. The following considerations are valid for both module types.

Tracks of charged particles are bent in the magnetic field according to their transverse momentum. Hits originating from low-momentum tracks are displaced further on the two sensors. By defining a search window around the hit in the inner sen-

[☆]On behalf of the CMS Tracker Collaboration

Table 1: Tuned geometrical parameters of the trigger module geometry [3].

tracker layer	strip pitch / μm	layer radius /cm	sensor spacing /mm	search window /strips
1	100	20	2.2	5
2	100	35	1.6	5
3	100	50	1.6	7
4	90	70	1.8	9
5	90	90	1.8	11
6	90	110	1.8	13

Figure 2: Transverse momentum spectrum of charged particles in the CMS tracker [4].

sor, hits from low momentum tracks can be distinguished from hits originating from high momentum tracks. Only the high momentum hits will be send out further to the trigger system. This results in a reduction of data rate by at least one order of magnitude, as can be derived from the momentum spectrum illustrated in figure 2. Further data reduction is achieved by switching to a binary readout.

The concept can only be applied, if the hits on both sensors are recognized efficiently. A detailed understanding of the signal distribution on the sensors, especially after radiation induced degradation of the sensor performance, is important for the optimization of the concept. A simulation model has been developed, predicting the charge distribution on the readout electrodes after a particle incident. The model is based on measurements of charge collection properties conducted on several irradiated sensors at different operation conditions in lab and testbeam studies.

3. Drift simulation model

The aim of the presented model [3] is to predict the charge distribution on the readout electrodes after a particle incident on the sensor. According to the track or laser incident (incidence angle, wavelength, ...), charges are created in the silicon volume, as depicted in figure 3a. After that, each individual carrier is propagated following the drift in the electric and magnetic field towards the readout electrodes. A one-dimensional parameterization of the electric field distribution $E(z)$ along the sensor depth z is used [5]:

$$E(z) = \frac{U_{\text{bias}} - U_{\text{fd}}}{d} + 2 \frac{U_{\text{fd}}}{d} \left(1 - \frac{z}{d}\right)$$

where U_{bias} is the applied reverse bias voltage, U_{fd} the full depletion voltage of the sensor and d the sensor thickness. The

(a) Placement of charges after a laser incident. (b) Electric field and electron drift mobility as a function of sensor depth at 300 V bias. The full depletion voltage of the sensor is 250 V.

Figure 3: Drift simulation model.

drift velocity of the particles is obtained using the Canali mobility model [6]. Figure 3b illustrates an example of the electric field and drift mobility distribution in a non-irradiated 300 μm thick sensor at 300 V applied bias.

4. Charge collection in irradiated silicon sensors and validation of the simulation model

In order to find a suitable silicon base material and sensor technology, the CMS Tracker Collaboration performed an extensive R&D campaign [7]. In the course of this campaign, besides electrical characterization of the sensors before and after irradiation, several different studies on charge collection properties of silicon sensors have been conducted and have been used to validate the outlined drift simulation model. For this work, measurements of the collected charge as a function of irradiation fluence, space-resolved testbeam measurements, Lorentz angle measurements and a projection to the binary readout are of importance.

4.1. Charge collection efficiency

The overall charge collection efficiency has been studied on pad sensors using infrared lasers, which penetrate the whole sensor thickness, and with electrons emerging radioactive sources on strip sensors. Figure 4 illustrates the total amount of collected charge on 300 μm and 200 μm thick n-in-p float-zone sensors as a function of the irradiation fluence. In the non-irradiated state, the most probable value of the collected charge of the 300 μm thick sensors is around 23 000 electrons, while the thin sensors give a signal of about 15 000 electrons, resulting in the usual MIP ionization signal in silicon of around 75 electrons/ μm . For all devices, the collected charge decreases because of radiation induced damage. At high fluence above $\approx 1 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$, the collected charge of 300 μm thick sensors is no longer above that of 200 μm thick sensors at 600 V bias voltage due to the faster increase of the full depletion voltage in thick devices.

200 μm thin sensors allow the reduction of the material budget in the tracking volume, one the one hand directly by the

Figure 4: Charge collection as a function of irradiation fluence on 300 μm and 200 μm thick n-in-p float-zone sensors.

reduction of silicon material, on the other hand by the reduced demands on the heat conducting periphery due to the reduced leakage current and thermal dissipation.

4.2. Testbeam

Testbeam studies allow the investigation of the efficiency and spatial resolution of a sensor, and the variation of the track incidence angle in a controlled way. In addition, due to the high resolution of the reference telescopes, a sub-strip resolved analysis of charge collection properties is possible. In the scope of the CMS Tracker sensor campaign, the performance of several irradiated strip sensors has been studied using a 4.6 GeV electron beam at DESY. The position dependent charge collection has been investigated and compared to the results of the described simulation model.

Charge created by tracks hitting the sensor directly at a readout strip is collected mostly by that single strip, whereas charge created by tracks passing between two strips is shared among these two strips. This is the reason for the position dependence of the average cluster size (5σ -seed cut, 2σ neighbor cut), as illustrated in figure 5a for a 200 μm thick proton irradiated ($1.5 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$) float-zone n-in-p sensor with p-spray strip isolation at 600 V and -20°C with perpendicular track incident.

Besides the cluster size, also the total amount of collected signal and the signal on the leading strip show a dependence on the track position, as illustrated in figure 5b. The signal of the leading strip is directly correlated to the average cluster size. In large clusters, less charge is collected by an individual strip. Although the total cluster signal is in the order of 10 000 electrons, and with that by far large enough for a proper operation of the sensor, the loss in the seed signal due to charge sharing bears the possibility of losing clusters during track reconstruction, resulting in a possible reduction of the efficiency of the sensor. The result obtained with the drift simulation model is represented by the colored bands and is in good agreement with the measured data.

4.3. Lorentz angle

Lab measurements are usually performed without the presence of a magnetic field. However, the drifting charge in the tracker is deflected by the Lorentz force exerted by the magnetic field present in the tracker volume. This deflection leads

Figure 5: Sub-strip resolved testbeam measurements on a 200 μm thick proton irradiated ($1.5 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$) float-zone n-in-p sensor with p-spray strip isolation at 600 V and -20°C with perpendicular track incident angle. The lines indicate the result of the drift simulation model.

Figure 6: Displacement of charge by the Lorentz force after a laser incident [8].

to a systematic shift of the reconstructed particle hit position and therefore has to be corrected during the reconstruction of the tracks. To estimate the evolution of the shift with operation conditions and radiation damage, dedicated measurements have been performed on irradiated strip sensors in a superconducting magnet at fields of up to 8 T [8]. Electron-hole pairs are created in the sensor by backside illumination with a short infrared laser pulse. By variation of the magnetic field, bias voltage and temperature, the deflection of charge carriers during the drift to the readout strips has been studied. Figure 6 illustrates the distribution of charge on the readout strips as a function of the magnetic field in the range of 0 T to 8 T. A shift towards lower strip numbers and a broadening of the charge distribution due to the deflection in the magnetic field is visible.

Figure 7 depicts the dependence of the Lorentz shift of electrons on the bias voltage. As long as the applied bias voltage is smaller than the full depletion voltage, the shift is rising with the bias voltage due to the expansion of the depleted depth. Above full depletion, the shift decreases again due to the reduction of the carrier mobility.

Especially the evolution with irradiation fluence will be different for the different layers in the detector. The shift has to be corrected at track reconstruction. Figure 8 depicts the shift of electrons as a function of the irradiation fluence. The reduction of the shift can be attributed to a rise in the full depletion voltage of the sensors. Because of that, a correlation to the annealing state of the sensor is visible. During annealing, the electric field distribution in the sensor changes due to changes of the full de-

Figure 7: Lorentz shift of electrons as a function of the applied bias voltage and irradiation fluence. The lines indicate the prediction by the drift simulation model.

Figure 8: Lorentz shift of electrons at 600 V bias as a function of the irradiation fluence and equivalent room temperature (RT) annealing. The lines indicate the prediction by the drift simulation model.

pletion voltage. For that, also the Lorentz shift is altered with annealing.

Overall, the distributions are reproduced by the drift simulation model.

4.4. Binary readout

Because of constraints on the available bandwidth, the new readout-chip implements a binary readout. This means, that the signal height information from each strip is compared to a programmable threshold level in the front-end chip and only the result of the comparator output bit is send out of the detector. The threshold level has to be chosen carefully during data taking. In opposite to the currently used analog readout, no tuning of the threshold levels during the offline reconstruction is possible.

The properties of the read out charge distribution and the detector efficiency depend on the threshold level. To investigate the influence of the binary readout on the sensor performance, data taken with an analog readout using a fast readout system (ALiBaVa¹ [9]) and a Sr90 β -source has been reanalyzed, applying a binary cut to the analog signal distribution. This way, the binary cut in the readout chip can be emulated.

Figure 9a illustrates the average cluster size as a function of the applied threshold. At high threshold levels, most clusters are composed of single strips, as an eventually shared charge to the neighboring strips is too small to pass the threshold and the cluster size approaches a value of 1. Towards lower threshold, more and more neighbor strips can pass the threshold and the

Figure 9: Binary reanalysis and threshold scan on data obtained with an analogue readout system.

average cluster size increases steadily. At very low threshold, the distribution gets dominated by noise hits, and the average cluster size increases dramatically.

In figure 9b, the number of identified hits using the binary interpretation is compared to the number of hits obtained using the analog analysis of the data applying a seed cut of five times the width of the noise distribution. A value of 100 % indicates, that the same number of hits has been identified by both algorithms and that the binary analysis is as efficient as the analog one. In this example, this is the case for threshold values between 3000 electrons and 5000 electrons, as indicated by the green area. For higher threshold values, more and more clusters fall below the threshold limit and are not identified anymore, and the efficiency decreases. Towards low thresholds, the distribution gets dominated by noise hits, and the relative number of (mis-)identified hits increases rapidly.

Overall, the measured results are reproduced by the drift simulation model, justifying the approximations applied.

5. Performance of the trigger module

After successful validation of the simulation model on measurement results, it can be used to study the trigger module concept. To obtain the correct correlation of the track impact angle to the particle transverse momentum p_T , a Geant4 simulation of a single module stack in a magnetic field has been set up. The Geant4 hit information is used as input for the drift model. The resulting charge distribution on both sensors is compared to a binary threshold and the correlation logic is applied. As a result, the trigger response as a function of the particle momentum is obtained.

To tune the module parameters like the size of the correlation window, a non irradiated module has been investigated. After tuning, a similar turn-on for all six tracker layers in the range of $1 \text{ GeV } c^{-1}$ to $2 \text{ GeV } c^{-1}$ has been obtained, as illustrated in figure 10. The geometric parameters are listed in table 1. Using this, the modules respond efficiently to high momentum particles, while low-momentum particles are rejected effectively.

Figure 11 illustrates the result of a testbeam measurement on a prototype module in an electron beam at DESY [10]. As the testbeam has been performed without magnetic field, the incidence angle was altered by tilting the module relative to the

¹A Liverpool Barcelona Valencia

Figure 10: Simulated trigger efficiency of the six layers of the new CMS tracker as a function of the particle transverse momentum. No radiation damage is taken into account.

Figure 11: Trigger efficiency as measured on a prototype module in a test beam by rotating the module [10].

beam axis. Assuming a certain distance from the interaction point, the incidence angle can be translated to a transverse momentum of the impact particle. In figure 11, a radius of 75 cm has been used for the transformation. As for the simulated data, a steep turn-on of the trigger efficiency in the vicinity of $2 \text{ GeV } c^{-1}$ is observed, demonstrating the correct implementation of the correlation logic in the readout chip.

Taking into account the radiation damage corresponding to 3000 fb^{-1} integrated luminosity for each individual layer, as given by table 2, the efficiency of the individual layers may change. To compensate for the increase in the full depletion voltage and noise and for the loss in charge collection efficiency due to carrier trapping, 600 V bias have been applied in the simulation. The resulting curves are shown in figure 12. To maintain a high efficiency, the threshold level has been reduced from 5000 electrons to 4000 electrons.

In order to find a suitable operation point, the phase space of threshold and detector noise has been scanned. For each combination, the detector inefficiency and the misidentification probability are evaluated. If the threshold is chosen too high,

Table 2: Simulation parameters used for the simulation after irradiation [3].

tracker layer	expected fluence [11] after 3000 fb^{-1} / ($n_{\text{eq}}/\text{cm}^2$)	collected signal / electrons	CCE / %
1	1.2×10^{15}	10250	73.2
2	5.75×10^{14}	12200	87.1
3	3.75×10^{14}	12800	91.6
4	2.4×10^{14}	13250	94.6
5	1.77×10^{14}	13450	96.0
6	1.5×10^{14}	13550	96.6

Figure 12: Simulated trigger efficiency of the six layers of the new CMS tracker as a function of the particle transverse momentum. Radiation damage is taken into account by reducing the collected charge and increasing the detector noise. To maintain a high trigger efficiency, the binary clustering threshold has been lowered to 4000 electrons.

Figure 13: Threshold-noise scan of the module performance. Red areas are excluded either by high noise occupancy or inefficiency in the track identification.

the inefficiency increases. The limit for acceptable operations has been set to 1 % of missed tracks. If the threshold is chosen too low, correlations induced by noise hits may occur and the detector might misidentify a low momentum particle track as a high momentum track. This ambiguity complicates the trigger decision and track reconstruction. The acceptable limit of misidentified tracks has been chosen to be 2 %.

Figure 13a illustrates the phase space for a non irradiated module. In the red area, at least one of the criteria is violated, while in the blue area, both criteria are fulfilled simultaneously. In this region, an efficient operation of the module concept is possible. For the non irradiated case, the operation range is large because of the high detector signal. With radiation induced damage, the signal gets reduced and the operation window shrinks, as illustrated by figure 13b for a module at 60 cm radial distance from the interaction point after 3000 fb^{-1} delivered luminosity. As an example, a read-out noise value of 1200 electrons, a missed track rate of at most 1 % and a misidentified track rate of at most 2 % have been chosen. By applying a threshold in the order of 4000 electrons, both criteria can be fulfilled.

6. Summary and conclusion

The CMS Outer Tracker will be replaced by 2023. The main design challenge is the necessary contribution to the first trigger stage of CMS. For that, a new module concept based on

the correlation of hits in two closely stacked sensors is pursued, allowing data reduction by a simple discrimination of the particles transverse momentum. To find a suitable sensor layout and silicon base material, the CMS Tracker Collaboration initiated a large sensor R&D campaign in 2010. In the scope of this campaign, several different measurements on the charge collection properties of irradiated silicon sensors have been performed. The results have been used to develop a simple and fast simulation model which allows the prediction of the charge distribution on the readout strips of the sensor after a particle incident. Thereby, radiation damage effects and the Lorentz deflection in the magnetic field are taken into account. The model has been developed and extensively validated on the basis of various measurements. The simulation model allows the estimation of the possible operation range of the new trigger module concept. The phase-space of binary threshold and detector noise has been scanned and the possible area of operation has been determined. Assuming the noise level to be around 1200 electrons, an effective operation threshold could be 4000 electrons. Measurements on prototypes of the readout chips indicate that a noise level below 1200 electrons will be achievable [10].

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