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The Upgrade of the CMS Outer Tracker

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Abstract

During the high luminosity phase of the LHC starting around 2025 (HL-LHC), the machine is expected to deliver an instantaneous luminosity of $5 \cdot 10^{34} \text{ cm}^{-2}\text{s}^{-1}$. A total of 3000 fb^{-1} of data is foreseen to be delivered, hereby increasing the physics potential of the LHC experiments significantly. However, this fivefold increase in luminosity compared to the design luminosity of the LHC will lead to a higher track multiplicity in the silicon tracking detectors of the experiments, and to severe radiation levels. In order to maintain physics capability, CMS will build a completely new tracking detector comprising a pixel detector and an outer tracker. Furthermore, information from the outer tracker will be used in the first level trigger of CMS to ensure a sufficient trigger rejection. For this purpose, CMS will use so-called p_T modules which will provide a momentum measurement at the module level. These modules consist of two back-to-back strip sensors for the outer layers, and a strip sensor and a macro-pixel sensor for the inner layers, respectively. This paper will introduce the concept of p_T modules and give an overview of the ongoing research and development activities concerning radiation hard silicon sensor materials.

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Abstract—During the high luminosity phase of the LHC starting around 2025 (HL-LHC), the machine is expected to deliver an instantaneous luminosity of $5 \cdot 10^{34} \text{ cm}^{-2}\text{s}^{-1}$. A total of 3000 fb^{-1} of data is foreseen to be delivered, hereby increasing the physics potential of the LHC experiments significantly. However, this fivefold increase in luminosity compared to the design luminosity of the LHC will lead to a higher track multiplicity in the silicon tracking detectors of the experiments, and to severe radiation levels. In order to maintain physics capability, CMS will build a completely new tracking detector comprising a pixel detector and an outer tracker. Furthermore, information from the outer tracker will be used in the first level trigger of CMS to ensure a sufficient trigger rejection. For this purpose, CMS will use so-called p_T modules which will provide a momentum measurement at the module level. These modules consist of two back-to-back strip sensors for the outer layers, and a strip sensor and a macro-pixel sensor for the inner layers, respectively. This paper will introduce the concept of p_T modules and give an overview of the ongoing research and development activities concerning radiation hard silicon sensor materials.

I. MOTIVATION

The Large Hadron Collider (LHC) at CERN delivered about 30 fb^{-1} of proton-proton collision data at center-of-mass energies of 7 and 8 TeV to CMS until the end of Run 1 in 2012. In order to enhance the physics potential for the experiments, several luminosity upgrades of the LHC accelerator complex are foreseen in the next ten years until the ultimate peak luminosity of $5 \cdot 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ is reached at a center-of-mass energy of 14 TeV around 2025 [1]. During this HL-LHC phase, at total of 3000 fb^{-1} of data is foreseen to be delivered to CMS with an expected average of 140 collisions per bunch-crossing, thus presenting an extremely challenging environment. Several components of the CMS experiment [2] will be upgraded in order to cope with these conditions while retaining the performance of the current detector [3].

II. THE UPGRADE OF THE CMS OUTER TRACKER FOR PHASE II

The design concept for the new CMS tracker [3], [4] is based on requirements to maintain efficient tracking capabilities under high luminosity conditions. With respect to the current tracker, the basic changes are increased granularity to maintain hit occupancies in the percent range, a reduced material budget in the active region as seen in Figure 1, delivery of tracker data to the level 1 trigger to significantly reduce the input rate to the high level trigger, and radiation tolerant silicon modules that will withstand 10 years of running at high luminosity. The overall baseline tracker design is shown in Figure 2. To aid forward jet reconstruction in the presence

of high pile up, the angular coverage of the CMS tracking system is extended significantly up to a pseudorapidity of $|\eta| = 4.0$, mainly by adding forward pixel stations. This will significantly improve the physics performance in key areas like vector boson fusion and vector boson scattering.

The concept of the outer tracker (OT) is based on p_T modules which consist of two silicon sensors mounted back-to-back for an on-module estimate of the transverse momentum of tracks. The tracker uses two-phase CO_2 cooling to remove heat from sensors and the electronics. This choice makes it possible to operate and maintain the tracker at -20°C , hereby reducing the effects of radiation damage to the silicon sensors. The material budget is also significantly reduced compared to liquid cooling. Power losses on the low voltage cables are reduced by using on-module DC-DC converters.

Fig. 1. Material budget in units of radiation length, X_0 , of the new CMS tracker for phase II, compared to the current tracker.

Fig. 2. Layout of the CMS tracking system for the HL-LHC. Outer tracker layers with modules consisting of two back-to-back strip sensors (2S modules) are shown in red, layers with modules consisting of a macro-pixel and a strip sensor (PS modules) are shown in blue. The pixel detector is depicted in green.

III. TRIGGER MODULES

The concept of a p_T module is illustrated in Figure 3. A module is composed of two parallel sensors which are separated by 1.6 to 4 mm depending on the position in the detector. Both sensors are read out by the same front-end chip. This allows discriminating high- p_T from low- p_T tracks based on the bending in the 3.8 T magnetic field of the CMS solenoid and by selecting hits within a search window. Track "stubs" are formed from the selected correlated clusters in the top and the bottom sensor. These track stubs are later combined off-detector to "tracklets" and to tracks. The p_T module for the outer layers consists of two strip sensors (2S), while in the inner layers, due to the higher track density, pixel-strip (PS) modules are used, consisting of a strip sensor and a pixel sensor with large pixels. Such a module is shown in Figure 4. The strip sensor of the PS module consists of 2 times 960 strips with 25 mm length and 100 μm pitch, while the macro-pixels are 1.5 mm times 100 μm in size. The signals from the strip sensor are processed by sixteen SSA (Short Strip ASIC) readout chips, while sixteen MPA (Macro-Pixel ASIC) chips process the signals from the macro-pixel sensor. The correlation of hits from the strip and pixel sensor and p_T stub building is done in the MPA, which sends out L1 track stubs for each 25 ns bunch crossing and stores the full module event data during the L1 latency of 12.5 μs .

In Figure 5, the cluster to stub multiplicity ratio is shown for barrel modules as a function of z (the coordinate along the direction of the beam) for a minimum bias Monte Carlo sample with an average of 140 pileup events, processed through the full CMS detector simulation. Depending on the layer in the tracker, a reduction of up to a factor of ten between clusters and stubs is reached.

A prototype PS module (Macro-Pixel Sub Assembly-light, MaPSA-light), based on a prototype MPA chip (MPA-light), is under development and will be available in 2015. A prototype 2S module has been built and the concept of track stub building was demonstrated in a testbeam at DESY [5]. This module uses a prototype version of the CMS Binary Chip (CBC). Figure 6 shows the stub finding efficiency as a function of equivalent transverse track momentum at a radius of 75 cm in the barrel, where the modules were tilted with respect to the beam in order to simulate tracks bent in the magnetic field of CMS. The efficiency curve results in a p_T threshold of 2.2 ± 0.1 GeV, which is in good agreement with expectation.

Fig. 3. Illustration of the track-trigger concept of correlated hits in closely spaced sensors. Tracks bent in the CMS magnetic field and clusters in both sensors are correlated to distinguish high and low p_T .

Fig. 4. PS module. The pixel readout chip, shown in gray, is sandwiched between the strip and the pixel sensor.

Fig. 5. Cluster over stub multiplicity in p_T modules as a function of module position.

Fig. 6. Stub finding efficiency of a prototype p_T module measured in a testbeam at DESY. The modules were tilted with respect to the beam axis to emulate the incidence angles of bent tracks in the absence of a magnetic field in the testbeam.

IV. RADIATION HARD SILICON FOR THE OUTER TRACKER

At the inner radius of the outer tracker, silicon modules are exposed to a mix of neutrons and charged particles (mainly pions) corresponding to 1 MeV neutron equivalent fluences of up to $\Phi_{eq} = 1.5 \cdot 10^{15} \text{ cm}^{-2}$ as shown in Figure 7. The corresponding ionizing dose at a radius of 20 cm is approximately 700 kGy. The operational properties of silicon sensors are

Fig. 7. Expected fluence in the CMS detector for full integrated HL-LHC luminosity [6].

strongly compromised at such fluences and CMS is spending considerable effort to identify an optimal choice of sensor material and to optimize the sensor design [7], [8], [9]. CMS has performed studies based on simple pad sensors, specialized test structures and prototype strip sensors implemented by Hamamatsu photonics (HPK) on silicon wafers varying in the crystal growth process for the substrate, the type of doping and the thickness. These structures were irradiated to fluences expected in the outer tracker and their electrical and charge collection properties were measured before and after irradiation with reactor neutrons and protons. Here we summarize the main outcome of this rich measurement program and the resulting design choices for the CMS outer tracker modules. Specifically, CMS decided in 2013 to use n-in-p sensors for the outer tracker. Apart from the well known advantage of depleting the sensor from the segmented side, irradiated p-in-n prototype sensors showed strong non-Gaussian noise. Figure 8 shows the distribution of the strip noise for a p-in-n and n-in-p prototype strip sensor, respectively, each irradiated to $\Phi_{eq} = 1.5 \cdot 10^{15} \text{ cm}^{-2}$. Simulations show that these noisy events are likely caused by discharges in high electric fields close to strip edges which are caused by a combination of the field in the sensor bulk after irradiation and positive charges in the silicon dioxide layer induced by ionizing irradiation. In Figure 9 the electric field at a bias voltage of 1000 V is plotted for a simulated p-in-n and n-in-p strip sensor, respectively. Defects in the band gap in the bulk part of the silicon sensor are simulated by an effective two-trap model. In each case, the electric field is simulated for two oxide charge densities, $Q_{ox} = 1 \cdot 10^{11} \text{ cm}^{-2}$ and $Q_{ox} = 1 \cdot 10^{12} \text{ cm}^{-2}$, the latter being a typical value for the inner layers of the outer tracker after 3000 fb⁻¹. In the n-in-p sensor, an increase in positive oxide

charges leads to higher electric fields close to the strip edges, whereas in the n-in-p sensor, the effect is the opposite: The field is reduced.

Fig. 8. Noise distribution for a p-in-n (left) and n-in-p (right) strip sensor after irradiation ($\Phi_{eq} = 1.5 \cdot 10^{15} \text{ cm}^{-2}$). The p-in-n sensor exhibits large non-Gaussian components to the noise.

Fig. 9. Simulation with Synopsis Sentaurus TCAD of the electric field 1.3 μm below the sensor surface for a p-in-n (left) and n-in-p (right) strip sensor after irradiation ($\Phi_{eq} = 1.5 \cdot 10^{15} \text{ cm}^{-2}$). The electric field is simulated for two oxide charge densities, $Q_{ox} = 1 \cdot 10^{11} \text{ cm}^{-2}$ (black curve) and $Q_{ox} = 1 \cdot 10^{12} \text{ cm}^{-2}$ (red curve). The bias voltage is 1000 V.

Apart from the type of doping of the sensors, the choice of bulk material and thickness has a strong impact on the stability of the charge collection over time in the experiment. The measured capacitance ($1/C^2$) is plotted in Figure 10 as a function of applied voltage for 200 μm thick n-in-p float zone and magnetic Czochralski pad diodes irradiated to $\Phi_{eq} = 1.5 \cdot 10^{15} \text{ cm}^{-2}$ for a variety of annealing times. While the curves lie virtually on top of each other for the magnetic Czochralski diode, a large variation in capacitance below depletion is visible for the float zone diode. The full depletion voltage extracted from capacitance-voltage (C-V) measurements is plotted in Figure 11 as a function of annealing time. Again, the magnetic Czochralski diodes show a very stable depletion voltage as a function of annealing time, while both n-in-p and p-in-n float zone sensors exhibit an initial decrease in depletion voltage and an increase for large annealing times (reverse annealing). The advantage of the magnetic Czochralski material is that it would be less important to keep the tracking detectors cold during maintenance periods to avoid reverse annealing. Moreover, by intentionally subjecting the sensors to some annealing, the leakage current can be brought down.

Figure 12 shows the charge collected by the seed strip (the strip with the highest pulse height in a cluster) in strip sensors irradiated to $\Phi_{eq} = 7 \cdot 10^{14} \text{ cm}^{-2}$ as a function of annealing time. The prototype strip sensors have a strip pitch of 80 μm ; results are shown for bulk thicknesses of 200 and 300 μm . Since the CMS readout chip will have binary readout, the charge of the seed strip is more relevant than that of the

Fig. 10. Measured capacitance ($1/C^2$) as a function of bias voltage for float zone (left) and magnetic Czochralski (right) sensors irradiated to $\Phi_{eq} = 1.5 \cdot 10^{15} \text{ cm}^{-2}$ for different annealing times. The measurements were performed at -20°C and a frequency of 1 kHz.

Fig. 11. Depletion voltage determined from capacitance-voltage measurements as a function of annealing time at 60°C for $200 \mu\text{m}$ thick float zone and magnetic Czochralski diodes. Also shown is the effective space charge concentration, N_{eff} , related to the depletion voltage by $|N_{eff}| = \frac{2\epsilon\epsilon_0}{e} \frac{V_{dep}}{d^2}$ where d is the thickness of the device.

total cluster. The measurements are performed at a reverse bias voltage of 600 V. The $300 \mu\text{m}$ thick float zone sensors exhibit a pronounced dependence of the signal on annealing time, which can be attributed to partial depletion of the sensors at large annealing times. Figure 13 shows the collected seed strip charge for a fluence of $\Phi_{eq} = 1.5 \cdot 10^{15} \text{ cm}^{-2}$ for $200 \mu\text{m}$ thick n-in-p strip sensors implemented on two different float zone wafers and on magnetic Czochralski silicon. Compared to other materials at the highest fluence expected in the outer tracker, $\Phi_{eq} = 1.5 \cdot 10^{15} \text{ cm}^{-2}$, the magnetic Czochralski n-in-p sensors show a very small dependence of the collected charge on annealing time. A stable charge collection as a function of annealing time is a great advantage taking the downtime during 10 years of HL-LHC operation into account. The final decision on the silicon crystal growth technique will depend on the stability of the charge collection at a reasonable operation voltage, as well as the cost. In Figure 14 the collected seed strip charge is shown as a function of particle fluence for $200 \mu\text{m}$ thick float zone sensors. On a log-log scale, the reduction of signal is roughly linear with fluence, implying that it follows a power law. In Figure 15 the seed strip signal for different strip sensors is shown as a function of the applied bias voltage after irradiation to $\Phi_{eq} = 1.5 \cdot 10^{15} \text{ cm}^{-2}$ after an annealing equivalent to 3300 hours at room temperature. At 600 V, the $200 \mu\text{m}$ sensors show a charge collection which is at least as high as for the $300 \mu\text{m}$ sensors. A relatively

Fig. 12. Seed strip charge for a mini strip sensor as a function of annealing time after irradiation to $\Phi_{eq} = 7 \cdot 10^{14} \text{ cm}^{-2}$ with a mix of protons and neutrons. The annealing was done at 60 or 80°C and scaled to hours at room temperature ($h_{eq} @ \text{RT}$, 21°C).

Fig. 13. Seed strip charge for a mini strip sensor as a function of annealing time after irradiation to $\Phi_{eq} = 1.5 \cdot 10^{15} \text{ cm}^{-2}$ with a mix of protons and neutrons. The legend is shown in Figure 12.

moderate bias voltage (for this high fluence) combined with thinner material leads to smaller bulk leakage current, power and noise. By going to higher voltages, the larger signal in thicker sensors can be recovered. While the type of doping is fixed to n-in-p, a final decision on the bulk material and thickness will depend on the outcome of a common CMS-ATLAS market survey currently underway. CMS is currently also exploring the production of sensors on 8 inch wafers to save cost.

V. CONCLUSION

As a consequence of a very challenging environment in terms of radiation damage and particle density and rates, CMS will build a completely new tracking detector for the high

Fig. 14. Seed strip charge as a function of fluence for 200 μm thick float zone sensors.

Fig. 15. Signal measured on the seed strip as a function of the applied bias voltage for strip sensors after irradiation to $\Phi_{eq} = 1.5 \cdot 10^{15} \text{ cm}^{-2}$ and after annealing equivalent to 3300 hours at room temperature. The legend is shown in Figure 12.

luminosity phase of the LHC. The outer tracker is based on trigger modules consisting of back-to-back strip sensors (2S modules) and strip and macro-pixel sensors (PS modules). The concept of finding track stubs for triggering could be established with a prototype 2S module, based on a prototype version of the CBC readout chip and a small sensor, while a prototype PS module is under development.

CMS will use n-in-p sensors for the detector modules in the outer tracker. While 200 μm thick sensors processed on a magnetic Czochralski substrate showed very stable charge collection as a function of annealing time after irradiation, the final decision on the crystal growth process for the substrate and on the thickness will depend on a common ATLAS-CMS market survey currently under way.

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