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The CMS Tracker Phase-2 Upgrade for the HL-LHC Era

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Abstract

In the mid of the next decade, the LHC will be upgraded to the High Luminosity LHC (HL-LHC) which will result in a significant increase in luminosity. To fully exploit the high luminosity conditions, the CMS detector will be upgraded as well which is referred to as the CMS Phase-2 Upgrade. Within this upgrade campaign, the tracking detector of CMS will be completely renewed. One of the key aspects of the upgrade are newly designed modules providing transverse momentum information to the L1 trigger at 40 MHz. The silicon sensors will feature higher radiation tolerance than those used in the present tracker. The module design, sensor R&D and future Tracker layout will be discussed in this paper.

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The CMS Tracker Phase-2 Upgrade for the HL-LHC Era

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Abstract. In the mid of the next decade, the LHC will be upgraded to the High Luminosity LHC (HL-LHC) which will result in a significant increase in luminosity. To fully exploit the high luminosity conditions, the CMS detector will be upgraded as well which is referred to as the CMS Phase-2 Upgrade. Within this upgrade campaign, the tracking detector of CMS will be completely renewed. One of the key aspects of the upgrade are newly designed modules providing transverse momentum information to the L1 trigger at 40 MHz. The silicon sensors will feature higher radiation tolerance than those used in the present tracker. The module design, sensor R&D and future Tracker layout will be discussed in this paper.

Keywords: CMS Phase-2 Upgrade, High Luminosity LHC, CMS experiment, CMS Tracker, p_T -modules.

1 Introduction

During the third long shutdown period (LS3), scheduled to start in 2024, the LHC will be upgraded to the High Luminosity LHC (HL-LHC), increasing its instantaneous luminosity by a factor of ~ 5 to a value of $5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ [1]. This will allow the CMS detector to collect an integrated luminosity of 3000 fb^{-1} after 10 years of HL-LHC operation. To benefit from the high luminosity conditions and due to current design limitations in terms of pileup and radiation damage, the CMS Tracker (pixel and strip detectors) will be replaced.

The necessity for an upgrade of the CMS Tracker is based on the fact that the current Tracker will have reached the end of its designed lifetime until LS3. The accumulated radiation damage in the sensors will result in a drastic increase in leakage current which cannot be reduced by cooling anymore. Therefore, one of the main requirements for the Tracker upgrade is the integration of more radiation hard silicon sensors. In the Inner Tracker, where the pixel modules will be installed, a fluence of up to $2.3 \times 10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$ is expected. In the Outer Tracker, where macro-pixel and strip sensors will be used, a fluence of $1 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ is expected. An expected pileup of 140 to 200 collisions per bunch crossing on average demands for an increased granularity to keep the occupancy at the percent level. Furthermore, the material budget will be decreased which reduces multiple scattering. The physics capabilities will benefit from an increased tracking

acceptance up to a pseudorapidity of $|\eta| = 4$. Finally, the so-called track trigger concept will be introduced. This concept is based on new types of modules able to provide information to the L1 trigger at the HL-LHC bunch crossing frequency of 40 MHz. This functionality is essential for maintaining the physics performance at high event rates. A detailed description of the Tracker upgrade will be given in the technical design report which is expected to be published by the end of 2017.

2 Layout of the CMS Phase-2 Tracker

The basic structure of the future Tracker is very similar to the current one. In particular, the same concept of barrel and end caps will be used. The pixel

Fig. 1. Sketch of one quarter of the Phase-2 Tracker. The pixel detector is composed of modules with two readout chips (green) and four readout chips (orange). Blue lines indicate the PS modules and red lines the 2S modules.

detector will be composed of modules featuring two readout chips and modules featuring four readout chips, located at different locations inside the Tracker (Fig. 1). Compared to the current pixel detector, additional discs on each end increase the tracking acceptance up to $|\eta| = 4$. In order to maintain a low occupancy at high pileup conditions, the pixel cell size will be reduced by a factor of six. Currently, planar pixel sensors produced on 6-inch n-in-p wafers are foreseen. The option of using 3D sensors providing a high intrinsic radiation hardness is currently being investigated as an option for the innermost layers.

The Outer Tracker will be composed of PS modules, made of one strip sensor on one macro-pixel sensor, in the inner regions, and 2S modules, made of two strips sensors, in the outer regions (Fig. 1). Some of the modules located in the first three barrel layers are tilted with respect to the beam axis, where the tilt angles increase towards the end caps. This innovative design improves the geometrical efficiency for the track trigger. The future Outer Tracker will be comprised of 7680 2S modules and 5616 PS modules in total.

3 The Track Trigger Concept

During the CMS Phase-2 Upgrade, the L1 trigger of CMS will be upgraded as well in order to maintain the capability of an efficient triggering under high pileup conditions. In particular, the L1 trigger rate will be increased to 750 kHz and the L1 trigger latency to 12.5 μ s. However, at an estimated pileup of 140 events, a much higher L1 acceptance rate would be required, which is not feasible. To overcome this issue, information on the particles' transverse momentum, p_T , measured in the Tracker will be included in the L1 trigger decision.

Fig. 2. Concept of the track trigger showing a schematic cross section of a two sensor module. The individual boxes represent the strips or macro-pixels. The boxes marked in green define the acceptance window. High p_T particles, hitting the sensors within the acceptance window, generate so called stubs.

The modules of the future Outer Tracker will be composed of two stacked and closely spaced silicon sensors with parallel strip orientation (Fig. 2). Due to the 3.8 T magnetic field of CMS, the tracks of traversing charged particles are bent. The curvature and therefore the hit positions on the stacked sensors is determined by the particles' p_T . Correlating the hit positions on both sensors enables an on-module p_T discrimination. Hit pairs of particles with a p_T above a certain threshold are referred to as stubs. The information on the stubs will be sent to the L1 trigger at a frequency of 40 MHz. A p_T threshold of ~ 2 GeV will reduce the L1 trigger rate by at least one order of magnitude.

4 The p_T Modules

Two different types of modules, both providing the p_T discrimination functionality, will be implemented in the Outer Tracker. The outer layers will be equipped with the so-called 2S modules, which consist of two identical silicon strip sensors with an area of 10 cm $\times$ 10 cm, a strip pitch of 90 μ m and a strip length of 5 cm (Fig. 3). In total, 16 CMS Binary Chips (CBCs) [2] read out the signals from the 2 $\times$ 2032 strips. In contrast to the currently used APV25 readout chip, the CBC

Fig. 3. Exploded view of the 2S module (left) and PS module (right) with a description of the single components.

provides only binary data. Besides data readout, the CBC also performs the hit correlation. The strips of the sensors are wire bonded to a flexible printed circuit board which routes the signals of both sensors to the CBCs. This front-end hybrid accommodates the CBCs and a concentrator ASIC (CIC) which buffers and aggregates the data of the CBCs. The service hybrid is equipped with DC/DC converters providing power to the module and a Low-power GigaBit Transceiver (LpGBT) for serializing and deserializing of data and for controlling the front-end ASICs via I²C. An optoelectronic transceiver converts the data to optical signals. Depending on the location of the module inside the Tracker, sensor spacings of 1.8 mm or 4 mm will be realised using aluminium carbon fibre (Al-CF) spacers.

The inner regions of the Outer Tracker will be equipped with so-called PS modules, which offer a higher granularity than the 2S modules (Fig. 3). The modules consist of a stacked strip and macro-pixel sensor separated by Al-CF spacers. Both sensors have an area $5 \text{ cm} \times 10 \text{ cm}$ and a strip or pixel pitch of $100 \text{ }\mu\text{m}$. The length of the strips (pixels) is 2.35 cm ($1467 \text{ }\mu\text{m}$). Depending on the position inside the Tracker, sensor spacings of 1.6 mm, 2.4 mm and 4 mm will be used. Two different ASICs will perform the binary readout of the two sensors. The strip sensor will be read out by eight Short Strip ASICs (SSAs) which are, like for the 2S module, attached to a flexible printed circuit board. The macro-pixel sensor will be read out by 16 Macro-Pixel ASICs (MPAs) [3] which are bump bonded directly onto the sensor and wire bonded to the flexible circuit board. The MPAs also perform the hit correlation on the PS module. A carbon fibre reinforced base plate, which is directly attached to the pixelated sensor, will be used for cooling. Similar to the 2S modules, the front-end electronics of the PS module will include the same CIC, LpGBT, optoelectronic transceivers and a DC/DC converter.

5 Silicon Sensor R&D

A large campaign containing several wafers of different base materials has been carried out in order to find the optimal sensor base material in terms of radiation hardness [4]. One of the outcomes is that n-in-p sensors show a higher signal than p-in-n sensors after the irradiation to HL-LHC fluences. Moreover, p-in-n sensors showed a non-Gaussian noise after irradiation, which results in fake hits. Thin sensors with an active thickness in the order of 200 μm to 240 μm are preferred, due to a higher signal and less leakage current after irradiation and a better annealing behaviour, as compared to thick sensors. All of these findings led to the decision to use planar, thin n-in-p type sensors for the future Outer Tracker.

Several prototype batches of full scale 2S sensors have been produced by Hamamatsu Photonics K.K. and Infineon Technologies Austria AG. The sensors showed satisfying characterisation results in terms of electrical properties [5], radiation hardness and performance in a particle beam. So far, only one batch containing small versions of macro-pixel sensors has been produced and characterized. Further prototype batches including full scale macro-pixel sensors will be available in the near future. A first prototype batch containing the strip sensors of the PS modules is expected to arrive by the end of 2017.

6 Summary

A brief overview on the CMS Tracker Phase-2 Upgrade mainly focusing on the future Outer Tracker was presented. The Tracker layout, module design, mechanics and sensor R&D are already very advanced and close to finalization. The innovative track trigger concept together with the L1 trigger upgrade will maintain or even improve the physics performance under high pileup conditions.

References

1. G. Apollinari et al.: High-Luminosity Large Hadron Collider (HL-LHC): Preliminary Design Report. CERN-2015-005, doi:10.5170/CERN-2015-005.
2. M. Raymond et al.: The CMS binary chip for microstrip tracker readout at the SLHC. *Journal of Instrumentation*, Volume 7, 2012.
3. D. Ceresa et al.: Macro-pixel ASIC (MPA): the readout ASIC for the pixel-strip (PS) module of the CMS Outer Tracker at HL-LHC. *Journal of Instrumentation*, Volume 9, 2014.
4. M. Printz on behalf of the CMS Tracker Collaboration: Radiation hard sensor materials for the CMS Tracker Phase II Upgrade - Charge collection of different bulk polarities. *Nucl.Instrum.Meth.* A765 (2014) 29-34.
5. A. König on behalf of the CMS Tracker Collaboration.: Exploring the quality of latest sensor prototypes for the CMS Tracker Phase II Upgrade. *Nucl.Instrum.Meth.* A845 (2017) 106-109.