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CMS Tracker Upgrade for HL-LHC: R&D Plans, Present Status and Perspectives

Fabio Ravera for the CMS Collaboration

Abstract

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CMS Tracker Upgrade for HL-LHC: R&D Plans, Present Status and Perspectives

F. Ravera^{a,*}, on behalf of CMS Collaboration

^aUniversity of Torino and INFN, Torino, Italy

Abstract

During the high luminosity phase of the LHC (HL-LHC), the machine is expected to deliver an instantaneous luminosity of $5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$. A total of 3000 fb^{-1} of data is foreseen to be delivered, with the opening of new physics potential for the LHC experiments, but also new challenges from the point of view of both detector and electronics capabilities and radiation hardness. In order to maintain its physics reach, CMS will build a new Tracker, comprising a completely new pixel detector and outer tracker. The ongoing R&D activities on both pixel and strip sensors will be presented. The present status of the Inner and Outer Tracker projects will be illustrated, and the possible perspectives will be discussed.

Keywords: Tracking detectors, Pixel, Strip, Level-1 tracking

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1. Introduction

The major achievement of the Large Hadron Collider (LHC) has been the Higgs boson discovery in 2012 [1, 2], but deeper investigations are needed in the Higgs sector and also on many other physics topics. Of particular interest are, for example, rare decays which can be enhanced by New Physics processes. To reach these goals, the luminosity of the accelerator will be increased at the end of 2022 to $\sim 5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ in order to collect 3000 fb^{-1} in the ten years of data taking of the High Luminosity LHC (HL-LHC). The increase of luminosity will be achieved replacing low- β triplets and installing crab cavities to optimise bunch-crossing overlaps.

2. Phase-2 CMS Tracker Upgrade

A first upgrade of the CMS detector, the so-called Phase-1, is foreseen for the end of 2016 with the installation of a new pixel detector [3]. Despite this upgrade, the Phase-1 tracker will not be able to stand the high Pile-Up (PU) of HL-LHC (expected average ~ 140 PU) and furthermore the muon- and calorimeter-based lowest level trigger (Level-1 or L1) will not be able to withstand the rates, due to PU and limited resolution. For these reasons, a completely new tracker detector, the so-called Phase-2 tracker, will be built. A proposed layout for the Tracker upgrade is shown in Fig. 1. The Tracker detector is composed of a Pixel Detector, with a coverage in pseudo-rapidity¹ extended

up to $\eta \sim 4$ (currently $\eta = 2.4$), and an Outer Tracker, able to provide L1-trigger information.

Figure 1: Sketch of one quarter of the proposed layout for the Phase-2 Tracker in the r - z plane. Pixel modules are shown in green, PS modules in blue and 2S modules in red.

2.1. Pixel Detector

The Phase-2 Pixel Detector is foreseen to be composed of 4 barrel layers and 10 + 10 forward disks. The ReadOut Chip (ROC) will be designed by the RD53 Collaboration [4] in 65 nm CMOS technology. The choice was driven both by the small pixel size achievable (50×50 or $25 \times 100 \mu\text{m}^2$), which allows to have a good high- p_T track resolution and bearable pixel hit rate ($\sim 1 \text{ GHz/cm}^2$ reduced to 100 kHz/pixel), and by its intrinsic radiation hardness ($\sim 1 \text{ Grad}$ is expected at a radius of 30 mm). The ROC will be designed with bump-bonding pads compatible with larger pixel sizes which could be used for outer layers of the pixel detector. Good progress has been done in the ASIC design by the RD53 Collaboration with the production of several test structures. ROC prototype submission is expected in 1-2 years.

The main requirement for the pixel sensors is the radiation hardness. In particular, the radiation fluence expected at 30 mm, the radius of the innermost layer, is $\sim 2 \times 10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$. The main reason of charge collection degradation at this level of fluence

*Corresponding author

Email address: fabio.ravera@cern.ch (F. Ravera)

¹The CMS coordinate system is oriented such that the x -axis points south to the center of the LHC ring, the y -axis points vertically upward and the z -axis is in the direction of the beam to the west. The azimuthal angle ϕ is measured from the x -axis in the x - y plane and the radial coordinate in this plane is denoted by r . The polar angle θ is defined in the r - z plane and the pseudorapidity is $\eta = -\ln \tan(\theta/2)$. The momentum component transverse to the beam direction, denoted by p_T , is computed from the x - and y -components, while the transverse energy is defined as $E_T = E \sin(\theta)$.

is trapping. Since the longer the drift distance the higher the charge lost by trapping, two R&D strands have been started for reducing the inter-electrode distance: thin planar sensors and 3D sensors. Thin planar sensors, with thicknesses between 100 and 200 μm , have already shown very promising performances after heavy irradiation [5]. Several submissions are expected this year to study small pixel feasibility, p-spray vs p-stop insulation, radiation tolerance and resolution in beam tests. Instead the basic concept of 3D sensors is to implement columnar electrodes such to decouple the sensor thickness from the inter-electrode distance. For this reason, this kind of sensor has a low depletion voltage (10 to 15 V before irradiation, depending on the electrode configuration) and intrinsically high radiation hardness. Also for these sensors very promising results have been obtained [6]. Two new 3D submissions are expected in 2015: one from CNM for investigating Phase-2 pixel size on thicker wafers by improving the aspect ratio between electrode radius and length, and the other from FBK to study thin 3D sensors (wafer thickness ~ 120 to $150 \mu\text{m}$).

Many simulations are ongoing for study the Pixel Detector layout. One of them is meant to investigate the best pixel cell configuration for each layer of the barrel and the disks. First observation is that pure square pixels in the barrel are not adequate because of a too high loss in impact parameter resolution, while they show good performances in the endcap disks. One possibility is to take advantage from the fact that the ROC can couple with larger pixel area, maintaining rectangular pixels in the barrel and square pixels in the endcaps, but with four times the pixel area in the two outer layers of the barrel ($50 \times 200 \mu\text{m}^2$) and in the outer disk modules ($100 \times 100 \mu\text{m}^2$). This will reduce by a factor ~ 2 the number of readout channels with respect to a pixel detector built with all modules with the smallest pixel size. Many other simulations are ongoing on the Pixel Detector layout to estimate hit resolution, occupancy and hit rates as a function of pixel pitch, sensor thickness and electronic threshold.

2.2. Outer Tracker

Taking advantage of the 3.8 T CMS magnetic field, the Phase-2 Outer Tracker will provide informations to the L1-trigger. This will be achieved by means of p_T -modules [7], composed of two closely-spaced silicon sensors read out by a common front-end ASIC capable to correlate the hits of the two sensors, as sketched in Fig 2. In this configuration, pairs of hits which form a “stub” compatible with a particle above a chosen p_T threshold are selected and dispatched to the L1 trigger system at the bunch crossing rate (40 MHz). All other hits are stored in the front-end pipelines waiting to be read out when the L1 trigger is accepted, at a rate of $\sim 750 \text{ kHz}$. Two different types of p_T -modules are foreseen for the Phase-2 Outer Tracker: Strip+Strip (2S) modules and Pixel+Strip (PS) modules.

The 2S module, shown in Fig. 3, is composed of two AC-coupled strip detectors (strip dimensions $90 \mu\text{m} \times 5 \text{ cm}$), both read out by the CMS Binary Chip (CBC) which performs the stub identification. Each 2S module has a sensitive area of

Figure 2: Low- p_T hit rejection in closely-spaced sensors where the “selection window” to define an accepted “stub” is shown in green.

$\sim 10 \times 10 \text{ cm}^2$ and a power consumption of ~ 4 to 5 W . Different 2S prototypes have already been produced and a beam test performed in December 2013 on a small size module (2 CBCs) before irradiation showed the expected stub finding efficiency [8]. New beam tests are foreseen on 2S prototypes before and after irradiation during summer and autumn of this year (2015). The next 2S ASIC submission is expected in the next year.

Figure 3: Exploded view of the 2S module components (left), 3D view of the assembled module (upper right), sketch of the FE Hybrid folded around its support (lower right).

The PS module, shown in Fig. 4, is composed by a DC-coupled pixel sensor (pixel area $100 \mu\text{m} \times 1.5 \text{ mm}$) read out by the Macro Pixel ASIC (MPA) and by a AC-coupled strip sensor (strip dimensions $100 \mu\text{m} \times 2.4 \text{ cm}$) read out by the Short Strip ASIC (SSA), which produces the stubs by merging the strip data with data from the pixel ASIC. The PS modules will have an area of $\sim 5 \times 10 \text{ cm}^2$ with a power consumption of ~ 6 to 8 W . Big efforts have been made to design and develop the PS module ASICs, tests of prototypes are ongoing and new designs are in progress.

Figure 4: Exploded view of the PS module components (left), 3D view of the assembled module (upper right), sketch of the FE Hybrid folded around its support (lower right).

Data from the CBC of the 2S module and from the SSA of

the PS module are buffered, aggregated and formatted by the Concentrator Integrated Circuit (CIC), currently under design, and then they are converted and sent to the tracker back-end by a 4.8 Gb/s bidirectional multi-mode optical link based on the low speed/low power grade of the GBT (LP-GBT). Low voltage to the ASICs is provided by an on-module DC-DC converter in order to power the detector at a higher voltage thus minimizing ohmic losses in the cables.

The Outer Tracker sensors will be subject to radiation fluences up to $1.5 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$. A strong R&D effort is being made to study radiation hardness on silicon Hamamatsu test samples of different materials (Float Zone, Magnetic Czochralski, epitaxial substrate and oxygen rich ones ($[\text{O}] > 2 \times 10^{16}$), different implants (n-in-p and p-in-n) and different thicknesses (300, 200, 100 and 50 μm). Results from irradiation campaigns [9, 10] showed promising performances of n-in-p implants, thanks to their higher radiation tolerance with respect to p-in-n. Furthermore, in Magnetic Czochralski materials the collected charge was observed to be independent of the annealing. Finally 200 μm thick sensors showed the same signal as 300 μm thick ones at highest doses but lower leakage current. To further reduce the leakage current the Outer Tracker will be operated at low temperature (-20°C). Various submissions to different vendors are ongoing to evaluate different processes, materials, design aspects (slim edge, width/pitch variations, inter-strip insulation) and to make a market survey. Further irradiation campaigns are foreseen.

Several simulation studies have been performed on the Outer Tracker layout. The baseline layout, shown in Fig. 1, is composed of 6 barrel layers and 5 + 5 endcap disks, and consists of 15508 detector modules (8424 2S and 7084 PS), for a total active surface of 218 m^2 , with 47.8 million strips and 218 million macro-pixels. The three inner barrel layers and the endcap disks up to a radius of $\sim 60 \text{ cm}$ will be equipped with PS modules thanks to their good z/η granularity. The remaining three outer barrel layers and disks will be equipped with 2S modules thanks to their lower cost and lower power density with respect to PS modules. The inter-sensor spacings have already been fixed as a function of the module position in the tracker. To reduce the number of different mechanical supports, six different spacings have been selected between 1.6 mm and 4.0 mm, while the stub selection window will be optimized module by module by Monte Carlo simulations. Studies of different Outer Tracker geometries using the tkLayout simulation tool [11] are ongoing, for example by tilting the PS modules in the barrel as a function of their η position, in order to reduce the material budget.

2.3. Level-1 Tracking

The capability of the Outer Tracker to select high- p_T stubs allows to have a Level-1 track reconstruction for particles above a selectable p_T threshold, foreseen to be $\sim 2 \text{ GeV}$. For the extreme challenge of reconstructing in the order of 100 tracks from ~ 15000 stubs within the trigger latency of $\sim 12.5 \mu\text{s}$, three strands are followed.

The first approach is called Associative Memories (AM) [12]. The idea is to use custom processors which contain pre-

loaded patterns ($\sim 10^8$) to be compared with the Outer Tracker hits. In this approach, the Tracker is divided into 48 angular regions (regional multiplexing), called trigger towers (6 in $\eta \times 8$ in ϕ). The hits matching a pattern are sent to the fitting algorithm, currently under definition, while the others are rejected. The production of the AM chip and mezzanine prototypes is in progress, but already before their delivery the AM functionality will be tested using FPGAs, where the firmware is already implemented. Optimization of the pattern bank and simulation of different fitting methods are ongoing.

The second approach is called Time Multiplexed Trigger (TMT) [13]. The concept is that multiple sources send data to a single destination for complete event processing which avoids boundaries and sharing of information between processors. The TMT reduces the requirements on synchronisation, which can be demanding in complex high-speed systems and, more important, the overall processing architecture is well matched to the operation of the FPGAs carrying out the processing. Since the size of the CMS Tracker is impossible to be handled by a single processor, the proposal is to divide the detector into 5 sectors in η . The implementation feasibility of the track finding algorithm is under study.

The third approach is the Tracklet Algorithm [14], in which FPGAs are used to implement a conventional road-based track search. Tracks are seeded by finding pairs of stubs in neighboring layers (tracklets). These tracklets are then projected to other layers to search for matching stubs. The track parameters are obtained using a linearized χ^2 fit. This concept, already tested on software, relies on the availability of a large number of memories interconnected with powerful Digital Signal Processing nodes in FPGAs to be translated into hardware. For this approach studies on electron tracking efficiency improvement, reduction of fake rate and on the performance in the barrel-endcap transition region are ongoing.

All these three R&D groups are working for producing demonstrators to verify their approaches on hardware. For this purpose, firmware for data sourcing is under development.

Figure 5: Level-1 tracking performances for single muons, electrons and pions.

The L1 track performances, evaluated from samples of single muons, pions and electrons, uniformly distributed in ϕ , η and p_T and overlaid with an average of 140 PU events, are shown in Fig 5 for the Tracklet Algorithm. Good tracking efficiency (Figs. 5(a) and 5(b)) has been obtained for single muons, while some degradation is observed for single electrons and pions due to interactions with detector material. The transverse momentum resolution (Fig. 5(c)) is $\sim 1\%$ for $\eta < 1$. The z coordinate resolution (Fig. 5(d)) is ~ 1 mm in the central region, close to the average separation of pile-up vertices. Similar figures of merit have been obtained for the AM approach.

3. Offline Performances

Some highlights of the expected Phase-2 offline tracking performances [15], compared with the ones obtained with the Phase-1 detector, are shown in Fig. 6. The tracking reconstruction efficiency for both muons (Fig. 6(a)) and $t\bar{t}$ events (Fig. 6(b)) using the Phase-2 Tracker with 140 PU events is as good as the Phase-1 efficiency with 50 PU events, and extends the $|\eta|$ range by about 1.5 units. The fraction of ghost reconstructed tracks (Fig. 6(c)) is slightly higher in the center but still at a bearable rate. Big improvement is obtained in p_T resolution both for 1 and 10 GeV muons. The performances shown here are evaluated using track seeds from the pixel detector while seeds from p_T modules are not considered and therefore improvements are expected.

Figure 6: Offline performance comparison between the Phase-2 Tracker with 140 PU events and the Phase-1 Tracker with 50 PU events.

4. Conclusions

The HL-LHC environment will require to replace the whole tracker for the CMS Phase-2 upgrade. The new tracker will be composed of a Pixel Detector and an Outer Tracker, and will extend the pseudo-rapidity coverage up to ~ 4 , improve the transverse momentum resolution and provide information for the L1 trigger.

The Pixel Detector is very challenging and currently under definition. Good progresses in designing the front-end ASIC have been achieved by the RD53 Collaboration and new prototype submissions are expected in the next years. Thin planar sensor and 3D sensor performance studies, especially after irradiation, are ongoing and several submissions are expected this year. Various simulations are being performed to define different aspects of the Pixel Detector layout.

For the Outer Tracker, innovative modules have been designed to identify on-module tracks above a certain p_T threshold, in order to comply with the required L1 track trigger capabilities. Prototypes already available will be tested this year with beam before and after irradiation. New prototypes will be available soon. The Outer Tracker layout configuration is almost defined, but many detailed simulations are ongoing.

For L1 track finding three strands are followed: Associative Memories, Time Multiplexed Trigger and Tracklet Algorithm. Good efficiency and transverse momentum resolution have been obtained with simulations, and hardware demonstrators are under development.

The final project will be described in a Technical Proposal expected in 2015, and the feasibility will be demonstrated in a Technical Design Report expected in 2017.

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