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The CMS Tracker Upgrade for the HL-LHC Tracking at Early Trigger Level

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Abstract

The performance of the tracker of the CMS experiment, comprising of a pixel and a strip detector, has so far been excellent, as reflected in the wealth of physics results produced so far. However, the foreseen increases of both the instantaneous as well as the integrated luminosity by the LHC during the next ten years will necessitate a series of upgrades of the CMS tracking detector. In 2016-17 the pixel detector will be exchanged, and around 2022 the whole tracker will need to be replaced, in order to be able to cope with an instantaneous luminosity of $5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ and an integrated luminosity of 3000 fb^{-1} , as expected for the High Luminosity LHC (HL-LHC). Experience at high luminosity hadrons collider experiments shows that tracking information enhances the trigger rejection capabilities while retaining high efficiency for interesting physics events. The design of a tracking based trigger for the HL-LHC is an extremely challenging task, and requires the identification of high-momentum particle tracks as a part of the Level 1 Trigger. The present status of this project is summarized, including the future tracker layout, the design of module prototypes, and the status of the front-end electronic components. Preliminary results of a simulated tracker layout equipped with stacked modules are discussed in terms of p_T resolution and triggering capabilities.

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The CMS Tracker Upgrade for the HL-LHC: Tracking at Early Trigger Level

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The performance of the tracker of the CMS experiment, comprising of a pixel and a strip detector, has so far been excellent, as reflected in the wealth of physics results produced so far. However, the foreseen increases of both the instantaneous as well as the integrated luminosity by the LHC during the next ten years will necessitate a series of upgrades of the CMS tracking detector. In 2016-17 the pixel detector will be exchanged, and around 2022 the whole tracker will need to be replaced, in order to be able to cope with an instantaneous luminosity of $5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ and an integrated luminosity of 3000 fb^{-1} , as expected for the High Luminosity LHC (HL-LHC). Experience at high luminosity hadrons collider experiments shows that tracking information enhances the trigger rejection capabilities while retaining high efficiency for interesting physics events. The design of a tracking based trigger for the HL-LHC is an extremely challenging task, and requires the identification of high-momentum particle tracks as a part of the Level 1 Trigger. The present status of this project is summarized, including the future tracker layout, the design of module prototypes, and the status of the front-end electronic components. Preliminary results of a simulated tracker layout equipped with stacked modules are discussed in terms of p_T resolution and triggering capabilities.

Keywords: ICATPP 2013; Proceedings; High Luminosity LHC; CMS; Silicon Tracker; Upgrade; Level 1 Trigger.

1. Introduction

As of September 2013, the experiments at the CERN Large Hadron Collider have accomplished important results, such as the observation of a new boson with properties consistent with the ones of the Standard Model Higgs

boson. On the other side, no evidence of new physics has been found yet. Several luminosity upgrades of the LHC are foreseen in the next decade, to enhance its discovery potential, to allow for precise measurements of the properties of the newly found boson, and to allow for the observation of rare processes below the current sensitivity level. The ultimate scenario, the so-called High Luminosity LHC, will present great challenges, as the average number of superimposed collisions per bunch crossing (pile-up) is expected to be approximately 140, with typical collider luminosities of $\mathcal{L} \simeq 5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$, which will allow one to integrate more than 3000 fb^{-1} over the years. To cope with these conditions and retain the performance of the current detector, several upgrades of the CMS experiment are planned, including additional coverage and redundancies of the muon system, higher granularity and resolution of the calorimeters, a new tracker with increased granularity, radiation tolerance, and hardware-based trigger capabilities (Level 1 or L1 trigger). Novel trigger strategies will be needed when the event rate starts exceeding the scale of GHz. As an example, the maximum allowed L1 muon trigger bandwidth, for nominal LHC conditions at 14 TeV, is 12.5 kHz, a rate that can be kept under control at $\mathcal{L} \simeq 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ using full muon system information, but which will become much larger at $\mathcal{L} \simeq 5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$, requiring also the use of information from the tracker to overcome this limitation (Fig. 1). Without upgrading the L1 trigger, the 12.5 kHz rate will be obtained imposing muon p_T thresholds at values larger than 60 GeV/ c , which will eventually kill the sensitivity of the experiment to the electroweak scale.

2. Tracker upgrade overview

The main requirements and guidelines for the tracker upgrade for the HL-LHC, called also “Phase 2” upgrade, in relation to the “Phase 1” upgrade expected in 2017-2019, can be summarized as follows:

- **Radiation tolerance:** the upgraded tracker must be able to operate efficiently up to a target integrated luminosity of 3000 fb^{-1} . This requirement must be fulfilled without any maintenance intervention for the outer tracker.
- **Increased granularity:** in order to ensure efficient tracking performance at high pile-up, the channel occupancy must be maintained around or below the percent level in all tracker regions, which requires higher channel density; 140 collisions per bunch

Fig. 1. The High-Level trigger single-muon trigger rates as a function of the p_T threshold for high luminosity. The rates are shown separately for Level 1, Level 2 (muon information only), and Level 3 (tracker information included), with and without isolation applied at Levels 2 and 3. The rate generated in the simulation is also shown.⁷ Rates expected at the HL-LHC may be estimated by a factor 10 scaling. The L1 resolution cannot reduce the data rate to cope with the $O(10)$ kHz bandwidth limit without losing the sensitivity to the EW scale. Such a resolution can be restored with the use of the tracker at L1 allowing then for sharp thresholds between 10 and 30 GeV/ c .

crossing is taken as target figure, with 200 collisions as upper limit.

- **Improved two-track separation:** the present tracker has degraded track finding performance in high-energy jets, due to hit merging in the pixel detector. In order to optimally exploit the statistics of the high luminosity operation, this limitation should be improved.
- **Reduced material in the tracking volume:** the performance of the current tracker is significantly limited by the amount of material, which also affects the performance of the calorimeters and of the overall event reconstruction in CMS. The exploitation of the high luminosity will greatly benefit from a reduced material budget of the tracker.
- **Robust pattern recognition:** track finding in high pile-up becomes increasingly more difficult and time consuming. The layout

of the upgraded tracker should enable fast and efficient track finding, notably for the High-Level trigger (HLT).

- **Contribution to Level 1 trigger:** the selection of interesting physics events at Level 1 becomes extremely challenging at high luminosity, not only because of the rate increase, but also because selection algorithms become inefficient at high pile-up. Therefore in order to preserve and possibly enhance the performance of CMS in a wide spectrum of physics channels, tracking information has to be used in the event selection, anticipating to Level 1 part of the reconstruction that is today performed in the HLT.
- **Extended tracking acceptance:** there are clear indications that the overall CMS physics performance would greatly benefit from an extended acceptance of the tracker and calorimeters in the forward region. This requirement mostly concerns the layout of the pixel detector.

The studies reported in the following are aimed at producing a Technical Proposal for the Phase 2 upgrade in 2014 (with the rest of CMS), and have Tracker Upgrade TDR fully finalized in 2016.

3. Trigger primitives from a silicon strip tracker

Due to the high granularity required for a silicon strip tracker at high luminosities, a large reduction of the data rate is required at the level of the front-end. Simulations of minimum bias events at 14 TeV show that more than 90% of charged particles that travel radial distances larger than 20 cm from the interaction point have a transverse momentum $p_T < 2 \text{ GeV}/c$. The design of a new tracker for the CMS Experiment at the HL-LHC is based on the concept of “ p_T -module”, a module composed of two parallel sensors, both read out by the same front-end capable of identifying hit pairs from high- p_T tracks. In the barrel section a lever arm between the sensors of 1.6 to 2.6 mm and a pitch of 90 to 100 μm , allows one to achieve a p_T resolution $< 20\%$ for $p_T \simeq 1.5 \text{ GeV}$ good enough to reject hits from $p_T < 1 \text{ GeV}$ with an efficiency $> 99\%$, thanks to the 3.8 T magnetic field of the CMS solenoid, by selecting hits in coincidence with each other within a small acceptance window. Such a pair of correlated hits is called “track stub”.

Two flavors of p_T -modules are being designed, one to be used in the outer part of the tracker and employing two identical strip sensors (2S module), one to be used at radii below 60 cm, where the track density

is higher, employing one strip sensor and one pixel sensor (PS module), both shown in Fig. 2. The 2S module is the most progressed in terms of design and prototyping. The hybrid board is the key element for module integration. Both sensors are wire-bonded at both ends to the hybrid board where 8 CMS Binary Chips (CBCs) are bump-bonded.² The CBC features an unparsified readout and hosts the stub finding logic. Each CBC reads signals from 127 strips and can handle one preloaded matching window (up to ± 8 channels), two preloaded offsets to compensate for module flatness and parallax (up to ± 3 channels), one maximum preloaded cluster width. Each CBC can output up to three stubs per bunch crossing. The current CBC version under evaluation is the second (CBC2).³ It features a $6.4 \mu\text{s}$ latency and a 100 kHz output rate, and it is the first version implementing the stub finding logic. Most recent tests of the CBC2 include the construction of a reduced-size p_T -module demonstrator equipped with an array of two CBC2s and two strip sensors, which has been used for source profile measurements with ^{90}Sr , tests of the correlation logic and read-out with cosmic rays, and noise measurements. A third version of the chip, the CBC3, is being designed and its submission is expected in 2014, with the major improvement being the possibility to handle half-strip resolution in the measurement of cluster position. A concentrator unit on the hybrid board will pack the data from the CBC array for up to 8 bunch crossings and send them to a customized version of the GigaBit Transceiver (GBT),⁴ featuring a 4.8 Gbps bandwidth, which acts as fast interface with the back-end. Each concentrator can output up to 12 stubs every 8 bunch crossings. While at this stage there is no working prototype for the concentrator chip, its functionality is emulated through FPGAs, allowing for tests and optimizations of the data packing algorithms. A big effort has been made in the optimization of the module support mechanics and thermal behavior. The current design makes use of a hollow unibody bridge made of Al-CF composite material, with a coefficient of thermal expansion matched to the one of the silicon, good heat drain and reduced material budget.

The PS module is characterized by different properties and problematics. The pixel sensor is bump-bonded to its dedicated ROC array (called Macro Pixel ASIC, or MPA⁵), which collects also data from the strip ROCs and performs the stub finding logic. The MPA is being designed in CMOS 65 nm and some of its blocks are being submitted to foundries for prototyping by end of 2013. The experience with 2S modules will be exploited as much as possible, with the biggest difference being the cooling: heat is

dissipated by the MPA between the two sensors, and the total power dissipation is higher than in 2S modules ($\simeq 5$ W against $\simeq 2.7$ W).

Fig. 2. Exploded view of the two module types being developed for the CMS tracker at the HL-LHC: 2S (left) and PS (right), not to scale.

The baseline option for the tracker layout chosen by the CMS Collaboration features six barrel layers up to $|z| < 120$ cm and five endcap disks on each side, as shown in Fig. 3. PS modules are used at radii smaller than 60 cm while 2S modules are used elsewhere. The layout has been optimized with *tkLayout*, a tool developed within CMS to evaluate and compare the properties and performance of different tracker layouts with analytical estimates of relevant figures-of-merit.⁶ Modules are placed in order to be hermetic with respect to stub finding efficiency. The typical number of stubs produced by each track ranges from 6 to 10, depending on the number of module overlaps found along the track trajectory.

Stub finding is simulated according to prescriptions derived from the ongoing hardware design. Stub finding efficiency for muon tracks is larger than 95% at the plateau in the whole tracker, with sharp turn-on in the range from 1.5 GeV/ c to 2.5 GeV/ c . Performance estimated with pions or electrons is worse, due to the larger interactions of such particles with the tracker material, as shown in Fig. 4. Another important number to evaluate is the expected output rate. Our simulations shows that even in the barrel layer with the highest occupancy, which is the one closest to the beamline, the average stub occupancy per module and per ROC is well within the CBC limitations. Expected data rate reduction is, on average,

Fig. 3. (Left) Layout of the currently envisaged CMS tracker for the HL-LHC. PS modules are pictured in blue while 2S modules are pictured in red. The option of an inner pixel detector with increased coverage up to $|\eta| = 4$, currently under evaluation, is shown too. (Right) Average number of modules hit by a track as a function of track η .

about 92% in modules with highest output rate. The true bottleneck will be the maximum output rate of the concentrators: also tails in the distribution of stubs per module matter, as interesting events may be characterized by narrow jets with tracks close in phase space, resulting in more than 20 stubs in one single module in one particular bunch crossing.

4. Track finding at early trigger level

Stubs are the trigger primitives produced by the tracker to be used for track finding at L1. The natural candidate technology for fast tracking in a generic tracker layout is pattern matching with associative memories (AM), an approach that dates back to the CDF Secondary Vertex Trigger. Current activities at CMS are focussing on the development of a flexible software emulation of the AM functionalities and the design of dedicated AM chips and boards. Both these activities must tackle three main tasks: fast data extraction from the front-end to the back-end, fast pattern recognition in hardware, fast track fit in hardware. The most demanding part of the AM emulation is the generation and handling of pattern banks. A pattern is defined as a set of gross-grain groups of strips per layer that define a road into the tracker. The size of these roads and the subdivision of the tracker into trigger towers must be optimized to balance the final size of the banks, track finding efficiency and pattern redundancy. Figure 5 shows the state of the art of the track finding efficiency obtained with AM emulation. This is close to 100% with some localized inefficiency in some of the sector overlaps. Although there is room for further improvement, this result is a proof-of-principle of the ability of AMs to reconstruct tracks in the HL-LHC conditions.

Fig. 4. (Top) Comparison of stub finding efficiency in the innermost (left) and outermost (right) layers of the barrel for different types of particles with full Geant4 simulation of the CMS tracker for the HL-LHC. Different matching windows and techniques are implemented to cope with the different module type, different sensor occupancy and get plateau efficiency at 2 GeV/c for MIPs. (Bottom) Expected reduction rate in the third layer of the barrel due to the implementation of stub finding in simulated minimum-bias events at an average pile-up value of 140.

5. Ongoing developments and required R&D

There are several ongoing developments involving all the aspects of tracker design and integration. The status of the main aspects of this R&D can be summarized as follows:

- **Sensors:** For the outer tracker sensors, substantial effort is required to optimize the production process and sensor design, and qualify possible vendors.

Fig. 5. Efficiency of the pattern recognition functionalities in the emulation of AM-based track finding with the CMS tracker under development for the HL-LHC.

- **New technologies for ASIC development:** The development of the front-end ASICs in deeper sub-micron ASIC technologies (130 nm and 65 nm) is a large ongoing effort. In particular, dedicated R&D is required to qualify 65 nm technology for use in the pixel detectors, develop tools and building blocks for the specific high radiation requirements.
- **Interconnection technologies:** The interconnection technologies required to build PS and 2S modules are substantially more advanced than in the present tracker: low-density industrial bump-bonding for hybrid assemblies with flip chip as alternative to wire-bonds, high-density low-mass substrates for hybrids. R&D is ongoing to identify technological options suitable for the requirements of the upgraded tracker and the volume of its production.
- **Back-end processing:** High-speed boards with high interconnectivity are required for the back-end processing to deliver the stubs to the Associative Memories and the identified tracks to the Level 1 trigger. Dedicated R&D is ongoing in this direction and towards the development of custom-made Associative Memory chips for the pattern recognition step.
- **Data links:** The upgraded tracker relies on high-speed low-power data links for the readout, and DC-DC converters for powering the front-end. Further improvements are needed in terms of performance and radiation hardness compared to the corresponding

“Phase 1” developments.

- **Cooling:** Two-phase CO₂ is the technology of choice for the tracker upgrade. Substantial development is needed to evolve from the current state of the art (2×15 kW system, for the “Phase 1” pixel detector), to the 80 to 100 kW range required for the whole Phase 2 tracker.
- **Materials:** Materials and glues need to be qualified to operate at higher radiation and lower temperatures compared to the present tracker. Novel materials such as carbon foams and aluminium-carbon compounds can help to realize lightweight assemblies fulfilling the more demanding requirements for thermal management; the use of such novel materials requires substantial R&D to develop and qualify assemblies suitable for the Tracker operating conditions.

6. Summary

The design of a track finding at early trigger level for the CMS experiment towards the HL-LHC upgrade is progressing fast, thanks to the wide effort put into this activity by several CMS institutions. A baseline option for the tracker layout has been chosen after a long process of evaluation and comparison. Prototypes of p_T -modules are being produced and evaluated. Stub finding performance and data rate evaluation are being constantly tuned to meet the constraints from hardware design and track finding emulation. Emulation of track finding is providing important figures of merit for the preparation of demonstrators. L1 tracks with realistic features are already used for the analysis of collision-like simulated events. Different ongoing studies aim at the definition of physical objects to trigger on, and eventually this will be the ultimate goal for track trigger activities because of its impact on CMS scientific production.

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