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Abstract

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Development of a Level 1 Track Trigger for the CMS Experiment at the High-Luminosity LHC

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Abstract

Over the next decade, several upgrades in the LHC and its injector chain will eventually increase the luminosity by up to a factor of 10 compared to the original design figure of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. In order to cope with the large number of interactions per bunch crossing, a novel tracking system for the CMS experiment will be designed and built. The new tracker will also provide information to the Level 1 trigger decision, in order to improve the ability of selecting interesting physics channels in a higher density environment. The CMS collaboration is developing a novel module concept (“ p_T -module”), where signals from two closely-spaced sensors are correlated in the front-end electronics, to select pairs of hits compatible with particle p_T above a certain threshold. Selected pairs of hits, called “track stubs”, represent between 5% and 10% of the overall data rate: such reduction factor enables the data processing at Level 1. Two main types of p_T -modules are being developed, one based on strip sensors, and the other coupling a strip sensor with a pixelated sensor, which provides also precise information in the z coordinate. The main features of the p_T -module options under development are reviewed, as well as the benchmark results from simulation studies.

Keywords: Tracking at high luminosities, Level-1 trigger, Silicon detectors

1. Introduction

By the end of 2012, the LHC experiments have not found any signal of physics beyond the Standard Model yet, in data collected at $\sqrt{s} = 7$ and 8 TeV with proton-proton collisions. The results which will be obtained during the future runs at 13 and 14 TeV will eventually set the basis for the future of particle physics studies with colliders. The CMS collaboration is preparing to pursue the search for the most rare processes with a high-luminosity LHC (HL-LHC). Such a scenario will be characterized by an increasingly challenging pile-up environment (PU), in which the current detector performance can be retained only through major upgrades of the different CMS subsystems.

The number of minimum-bias events per bunch-crossing, with a luminosity leveled to about $5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ at $\sqrt{s} = 14$ TeV, is expected to be about 140, with several thousands of charged particles traveling the tracking volume. In such a scenario, the Level 1 trigger (L1) rate at CMS is expected to exceed its design limit, which is currently 100 kHz [1]. With the current L1 based on primitives from muon system and calorimeters, the thresholds required to cope with the maximum allowed bandwidth would be too high. A remarkably better resolution is needed to keep the thresholds low and collect a significant amount of events for the CMS physics program. The inclusion of tracker information, which is currently used only at the High-Level trigger, in the L1 decision, can provide the necessary resolution, as shown in Fig. 1, left. This would be possible only with the design and construction of a novel tracking system, capable of providing information for the L1 trigger. Such tracker should maintain high reconstruction efficiency and low

fake rate, hence featuring high granularity to keep occupancy below a level ~ 0.01 , and it should withstand a harsh radiation environment. In addition, its performance as part of L1 should include a precise measurement of muon p_T to allow for a sharp threshold at $p_T \sim \mathcal{O}(10)$ GeV, the possibility to match track to calorimeter L1 candidates and isolate electrons, τ -leptons and photons, and the possibility to associate objects to their corresponding primary vertex to reduce fakes from PU.

Figure 1: Left: effect of increasing the p_T resolution in L1 and high-level muon triggers. A rough estimate of the behavior at HL-LHC can be obtained by rescaling the expected L1 muon rate, at nominal 14 TeV LHC conditions, by a factor 10. In such a case, only a tracker-grade resolution, such as the one of the L2 and L3 in HLT, can keep the threshold low enough to accept events of physical interest and the rate low enough to cope with the data-acquisition limits [2]. Right: p_T spectrum of the average number of tracks per event reaching a layer 25 cm from the beam line in simulated minimum-bias events. Less than 10% of the tracks have a p_T larger than 2 GeV/c. Imposing such a threshold at the front-end could reduce by a factor 10 the data rate to be processed by the L1 trigger.

2. The concept of Level 1 Track Trigger

The Track Trigger can be seen as a two-steps process. The first step aims at reducing the data rate at the front-end, by using cluster width and local p_T information, rejecting up to 95% of tracks from minimum-bias events, as shown in Fig. 1, right. The second step employs a real-time tracking facility that reconstructs tracks at L1 from the non-rejected hits.

The p_T -module concept is at the roots of Track Trigger. Such a module features two closely spaced silicon strip or pixel sensors and a front-end that can perform local p_T reconstruction measuring the relative transverse displacement of narrow clusters in the two sensors. This result can be achieved, in the current field of the CMS solenoid, with sensors separated by few mm and strip or pixel pitch of about $100\ \mu\text{m}$. Accepted pairs of clusters are called *track stubs*. A graphical representation of the process is shown in Fig. 2, including the kind of correction needed to compensate for the misalignment of hits due to the flatness of the modules and their orientation.

Figure 2: Left: sketch of the Track Trigger basic idea. A track with $p_T \approx 2\ \text{GeV}/c$, in the 3.8 T magnetic field of the CMS solenoid, produces hits in two closely spaced sensors, positioned at a distance of 30 to 100 cm from the beam line, which have a relative displacement in the transverse plane that can be measured with a pitch-to-separation ratio of about 1-to-10. Right: sketch of the position-dependent offset and matching window span in stub finding. The stub finder window is centered on the radial projection of the innermost hit onto the outermost sensor. In the areas which are far away from the center of the sensor, where the projection falls out from the channel corresponding to the innermost hit, an offset must be applied to preserve the stub finding efficiency.

There are three main types of p_T -modules under evaluation [3]. One type of module, called 2S (2-Strip-sensors), features two identical silicon microstrip sensors which share the same ROC array, which is designed to perform the stub-finding cluster correlation. The size of the strips in the current design of 2S modules is $90\ \mu\text{m} \times 50.2\ \text{mm}$. Two other types of modules, called respectively PS and VPS (Pixel-plus-Strip) couple a strip sensor to a pixelated sensor. The PS module features two separate ROC arrays for strips and pixels. The pixel ROC array is bump-bonded to the pixel sensor and designed to perform the stub finding cluster correlation. The size of the strips and pixels in the current design of PS modules are $100\ \mu\text{m} \times 23.1\ \text{mm}$ and $100\ \mu\text{m} \times 1.446\ \text{mm}$, respectively. The VPS module is a particular version of the PS module, featuring vertically integrated electronics (Vertical-PS). The VPS modules are being developed specifically for one particular layout, called the “LongBarrel”, which is dedicated to L1 track finding and which is composed of long interlocking rods (see Sec. 5 and Fig. 4).

Fig. 3 shows three-dimensional representations of 2S and PS modules.

The 2S and PS/VPS modules are complementary in a HL-LHC tracker layout. While all of them can perform the local p_T reconstruction necessary to implement the Track Trigger, the PS and VPS modules will additionally measure the position of the stubs, in the direction of the beam line, with a resolution of $O(1)\ \text{mm}$, at distances shorter than 60 cm from the beam line, where the track density is higher. This feature will help in identifying the primary vertex of the event and in isolating relevant trigger objects from the pile-up.

The development of 2S modules already established benchmarks in most of the critical aspects of the design, which will be summarized in this contribution; the design of PS and VPS modules is at an earlier stage, due to the exploration of new technologies to be used, such as CMOS 65 nm for the PS modules front-end and 3D vertical integration for VPS modules. For this reason, this contribution will mainly focus on the development of 2S modules.

Figure 3: Left: 2S p_T -module drawing with two ROC hybrids shared by the strip sensors and one service hybrid. Right: PS p_T -module drawing with two ROC hybrids for the strip sensors and two service hybrids. The pixel ROC array is bump-bonded to the pixel sensor and hidden in the picture. Strips are oriented top-left to bottom-right in the picture.

3. Mechanics and cooling

One of the main challenges in the design of a novel tracker module is represented by its mechanical support, which must be lightweight to minimize the amount of passive material, and which must be also optimally coupled to the pipes in which the cooling fluid flows.

The support structure of the p_T -modules is based on two bridges which keep the sensors aligned and separated by the chosen distance. Different options have been explored for the design of support bridges. In particular, the possibility of using a support bridge made of carbon-fiber (CF) strips coupled to graphite sheets and a foam spacer, joined to the cooling pipe with aluminum feet, has been studied. Such a design turned out to be at risk of shear stress, which could cause delamination of the graphite sheets and loss of thermal contact between the module and the aluminum feet. For this reason, the option of a hollow unibody bridge, made of composite Al-CF, is now being explored as a likely option, featuring analogous mechanical and thermal properties as those of the previous bridges, with the benefit of a much easier assembly process. A mock-up of a PS module is shown in Fig. 4, left, where the relative position of bridges and hybrids are clearly visible. The design

of the p_T -module mechanics includes the optimization of interconnections and positioning of service hybrids, and makes large use of finite element analysis to estimate thermal and mechanical properties of the different solutions.

A complementary approach, specific for the L1-oriented LongBarrel layout, and based on VPS modules, allows a track finding based on the creation of stub pairs in consecutive layers. Such a layout would be barrel-only, spanning the whole tracking volume with 2.7 m interlocking rods [4, 5]. Lightweight CF hollow rod prototypes, allowing all the services and cooling to run inside the rod volume, were already produced. A sample is shown in Fig. 4, right.

Figure 4: Left: mock-up of a PS module for module support evaluation and module packaging optimization. Right: prototype of a CF rod for VPS modules in the L1-oriented barrel-only tracker layout.

The design of the 2-phase CO₂ cooling, allowing to keep the modules working at the temperature of -20°C , is complementary to the design of the mechanics. Aluminum cooling blocks are being used to ensure good thermal contact between the module support bridge and the steel cooling pipe. Finite-element analysis is used to optimize the shape of cooling blocks, in order to retain only the part of the block which actually drains the heat, achieve a small thermal gradient, and keep the material budget low. Prototypes featuring different block shape and different means of coupling to the cooling pipe were produced and are being tested.

4. Front-end electronics and data transfer

The transmission of the large amount of data produced by a L1-capable tracker, given the limited amount of optical links available and the high granularity of the detector, will be possible only in a digital form. A sparsified read-out would be needed in order to digitize the pulse height at the front-end. This solution is non-manageable in terms of complexity of the ROC, and also will imply a slightly higher power dissipation than a non-sparsified read-out. One additional important reason for a non-sparsified architecture is that it allows a synchronous read-out.

The ROC currently being developed, the CMS Binary Chip (CBC), copes with these requirements, being based on a binary un-sparsified architecture specifically designed for the 2S p_T -modules [6]. The CBC is based on CMOS 130 nm technology, features 128 read-out channels and a latency of $6.4\ \mu\text{s}$. The CBC underwent beam tests at CERN SPS in October 2012,

reading out signals from fully-depleted 5 cm long p-on-n strips made by Infineon, featuring $80\ \mu\text{m}$ pitch. This setup was used to measure cluster width and beam profile downstream the UA9 telescope [7], at different incidence angles of the beam, as shown in Figure 5.

A new version of the CBC, the CBC2, was designed in 2012, featuring the capability to read simultaneously 127 channels from two different sensors and a stub finder based on cluster correlation [8]. Position-dependent matching windows, as large as 16 channels, and offsets, which take into account the asymmetry of matching windows due to the distance from the center of a flat sensor, as shown in Fig. 2, are programmed in the ROC. A problem which will be addressed in the future is the data sharing between neighbor ROCs. Preliminary tests and evaluation of the CBC2 are being performed in early 2013.

Figure 5: Comparison of beam profile measurements with the UA9 telescope and p-on-n microstrip sensor read by CBC.

The long-distance data transmission is managed by a Giga-Bit Transceiver (GBT), allowing simultaneous transmission of data from the front-end and calibration and maintenance of the ROC. The current GBT is designed in CMOS 90 nm and features a maximum optical bandwidth of 4.8 Gb/s with a 2.1 W power consumption. A new low-power GBT is being designed to be used in the p_T -modules, with an expected power consumption of about 0.5 W.

The constraints from the front-end design will allow a maximum of 3 stubs to be transmitted per bunch crossing and a maximum of 12 stubs every 8 bunch crossings. The optical layer should connect the front-end with the back end, which can be as far as 150 m away. In order to build a low-profile optical interface, a standalone module is being designed, optimizing the volume occupancy of the versatile transceiver (VTRx) into an aggressive packaging, which is currently limited by the size of the standard transmitter and receiver optical subassemblies (TOSA/ROSA).

An alternative scenario foresees the increase of the L1 bandwidth from 100 kHz to 1 MHz. In such a case, the read-out rate would exceed the limit of 40 Mb/s, implying therefore the need of sparsification and asynchronous read-out with timestamp, and the design of a new front-end.

5. Layout and simulation studies

Two main concepts for the tracker design are being evaluated, respectively called “LongBarrel” and “BarrelEndcap”. While

the latter is a layout made of PS and 2S modules arranged in a conventional layout, the LongBarrel features a barrel-only structure arranged in projective sectors. Track finding at L1, in such a layout, will be based on FPGAs: pairs of stubs in consecutive pairs are used as seeds and combined with additional stubs within the projective sector.

The optimization of these layouts relies on a standalone tool, called “tkLayout” [9, 10]. It can build a 3D model of the tracker, assigning the correct material to each module, and *a priori* estimates relevant figures of merit, such as occupancy, power consumption, material budget, tracking and trigger efficiency. This tool is useful in pre-optimizing the design, while detailed performance and integration with other CMS subsystems is based on a Geant4 simulation of the tracker. Both the tools emulate the main features and constraints of a realistic stub finder. Fig 6 shows the stub finding efficiency estimated with the two tools. Track finding simulation studies are also being performed for both the LongBarrel approach and for a L1 tracking based on associative memories for a more traditional tracker layout [11, 12].

Figure 6: Top: estimate of the stub finding efficiency with the tkLayout tool for a barrel-plus-endcap tracker layout for tracks with $p_T = 2.0$ GeV/c. Bottom: estimate of the stub finding efficiency using a Geant4 simulation of a barrel-plus-endcap tracker layout and tracks from muons with flat p_T spectrum in the barrel and endcaps, respectively.

6. Concluding remarks

The inclusion of Track Trigger at L1 is a challenge for the CMS experiment. Several complementary approaches are being investigated at all levels. The production of prototypes for each component of p_T -modules has already started as well as

their evaluation. The future steps in designing and prototyping p_T modules will tackle relevant aspects of the mechanics and electronics, including the design of a front-end in CMOS 65 nm. Moreover, the test of the CBC2 and the integration of an array of CBC2s are fundamental to complete the debugging of the stub finder. The impact of different designs and layouts on physics studies are being evaluated in view of the drafting of a technical proposal in 2014.

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