The Compact Muon Solenoid Experiment

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Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

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Operation and Performance of the Upgraded CMS Calorimeter Trigger in LHC Run 2

Pamela Renee Klabbers for the CMS Collaboration

Abstract

The Large Hadron Collider (LHC) at CERN is preparing for the physics program for Run 2. The center-of-mass energy has risen from 8 to 13 TeV and the instantaneous luminosity will increase for both proton and heavy-ion running. This will make it more challenging to trigger on interesting events since the number of interactions per crossing (pile-up) and the overall trigger rate will be significantly larger than LHC Run 1. The Compact Muon Solenoid (CMS) experiment has installed a two-stage upgrade to their Calorimeter Trigger to ensure that the trigger rates can be controlled and the thresholds can stay low, so that physics data collection will not be compromised. The first-stage upgrade is installed and includes new electronics and duplicated optical links so that the LHC Run 1 CMS calorimeter trigger is still functional and algorithms can be developed while data taking continues. The second-stage will fully replace the calorimeter trigger at CMS with AMC form-factor boards and an optical link system, and require that the updates to the calorimeter back-ends, the source of the trigger primitives, are also installed and operational. The stage-2 system's boards will utilize Xilinx Virtex 7 FPGAs and have hundreds of high-speed links operating at up to 10 Gbps to maximize data throughput. The integration, commissioning, operation, and performance of stage-1 for 2015 data taking and stage-2 for triggering in 2016 will be described.

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Operation and Performance of the CMS Level-1 Calorimeter Trigger Upgrade

P. Klabbbers for the CMS Collaboration, *University of Wisconsin - Madison*

Abstract—The Large Hadron Collider (LHC) at CERN has begun the physics program for Run 2. The center-of-mass energy has risen from 8 to 13 TeV and the instantaneous luminosity will increase for both proton and heavy-ion running. This will make it more challenging to trigger on interesting events since the number of interactions per crossing (pile-up) and the overall trigger rate will be significantly larger than LHC Run 1. The Compact Muon Solenoid (CMS) experiment has installed a two-stage upgrade to their Calorimeter Trigger to ensure that the trigger rates can be controlled and the thresholds can stay low, so that physics data collection will not be compromised. The first-stage upgrade is installed and includes new electronics and duplicated optical links so that the LHC Run 1 CMS calorimeter trigger is still functional and algorithms can be developed while data taking continues. The second-stage will fully replace the calorimeter trigger at CMS with AMC form-factor boards and an optical link system, and require that the updates to the calorimeter back-ends, the source of the trigger primitives, are also installed and operational. The stage-2 system's boards will utilize Xilinx Virtex 7 FPGAs and have hundreds of high-speed links operating at up to 10 Gbps to maximize data throughput. The integration, commissioning, operation, and performance of stage-1 for 2015 data taking and stage-2 for triggering in 2016 will be described.

I. INTRODUCTION

THIS year (2015) the Large Hadron Collider (LHC) at CERN started the Run 2 proton physics program. The repairs and consolidation of the magnet interconnections [1] over the Long Shutdown 1 (February 2013 to June 2014) have allowed the LHC to increase the p-p center-of-mass energy from 8 to 13 TeV. The instantaneous luminosity is expected to surpass that of LHC Run 1, and the number of interactions per crossing (pile-up) will be greater by a factor of 2 compared to that of LHC Run 1. The heavy-ion (Pb) program will also see increases in luminosity of 4-8 times previous runs. These changes will make triggering on interesting events even more challenging.

The original specification for the Compact Muon Solenoid (CMS) experiment was a maximum level-1 trigger rate of 100 kHz [2]. To exceed this, some detector systems (e.g. tracker) would have to undergo major upgrades. Instead, CMS has upgraded its trigger hardware so more sophisticated algorithms can be used instead of increasing thresholds to keep the trigger rate under control. The upgrade to the CMS

Trigger will include the calorimeter, muon, and global subsystems (a block diagram of the original trigger is in Fig. 1), but only the calorimeter trigger upgrade will be described.

Fig. 1. A block diagram of the CMS Trigger used during LHC Run 1. Calorimeter, muon, and beam monitoring (not shown) are part of the decision making tree. Upgrades to all the trigger sub-systems are underway. The calorimeter portion is on the left hand side of the diagram.

II. THE LEGACY CMS CALORIMETER TRIGGER

The LHC Run 1 CMS calorimeter trigger was built entirely of custom electronics. It was built in two stages, a Regional Calorimeter Trigger (RCT) [3] and a Global Calorimeter Trigger (GCT) [4]. The RCT comprises 18 9U custom backplane VME crates for receiving Trigger Primitives (TPs) in the form of an 8-bit transverse energy (E_T) and quality bit from over 8000 towers in the Hadronic, Forward, and Electromagnetic Calorimeters (HCAL, HF, and ECAL). It processes this information in parallel and each RCT crate sends 8 e/γ candidates' E_T (1×2 tower sums), 14 4×4 tower energy sums each with 3 bits to describe the energy deposits, and 8 forward towers with 8 quality bits to the 9U VME GCT. The GCT sorts the e/γ candidates further, finds jets, and calculates global quantities like Missing E_T . It then sends eight e/γ of two types, four each of Central, Tau, and Forward Jets, and several global quantities to the CMS Global Trigger (GT) for the final trigger decision.

III. THE HARDWARE

The hardware installation for the calorimeter trigger upgrade [5]–[8] has been done in two stages. Stage-1 used the existing RCT and replaced the GCT with a second level consisting of custom μ TCA hardware. A 9U optical Regional Summary Card (oRSC) (Fig. 2) was added to the RCT crates to transmit data optically to new hardware, while preserving

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P. Klabbbers is with the University of Wisconsin – Madison, WI, 53706, USA (e-mail: pamc@hep.wisc.edu).

the connections to the GCT. The oRSC has a Xilinx Kintex-7 FPGA for processing and 23 optical links that can send data out at speeds of up to 10 Gbps. The oRSC receives the 4x4 tower regional sums, 2x1 tower sums for e/γ finding, and quality bits from the RCT and sends them on two optical links at 10 Gbps to μ TCA boards to perform the global processing and readout of the data. The boards, called MP7s (Fig. 3) and CTP7s (Fig 4), are small multi-purpose boards with a powerful Xilinx Virtex-7 FPGA for processing. For connectivity, the MP7 has 72 input and 72 output links and the CTP7 has 67 input and 48 output links. The new trigger algorithms will implemented with these boards and the final jet, e/γ , and tau candidates, as well as global quantities will be sent to the upgraded GT.

Fig. 2. Optical Regional Summary Card (oRSC), a 9U VME card installed in the CMS RCT crates (18 in total). It converts 80 MHz parallel, differential ECL output to optical and provides multiple copies of data on optical links for parallel commissioning at link speeds of 10 Gbps and legacy trigger operation at 2 Gbps.

Fig. 3. Master Processor – Virtex 7 (MP7), the backplane connector to the left, 72 input and output links (Avago MiniPODs) left, the large Xilinx XC7VX690T FPGA, as well as module management, power modules throughout, dual QDR RAM (back of card), and firmware via MicroSD card or conventional PROM.

The stage-2 hardware was installed in parallel with the stage-1 and is scheduled to be ready for physics at the beginning of 2016. To be fully operational, the HCAL, HF, and ECAL back-end electronics had to be upgraded to optical outputs to be compatible with the new Stage-2 μ TCA Layer-1 boards, the CTP7s.

Instead of the present conventional pipelined trigger, stage-2 will use a new architecture with time multiplexing. For this, eighteen CTP7s will receive TPs at speeds of up to

6.4 Gbps from the calorimeters, time-order and send copies at 10 Gbps to 9 MP7s that work on one LHC crossing at a time, scanning the entire calorimeter by rows of towers in pseudorapidity and finding trigger object candidates. The results are sorted in a final de-multiplexing stage before being sent to the Global Trigger.

Fig. 4. Calorimeter Trigger Processor – Virtex 7 (CTP7), backplane connector on the left, the Xilinx ZYNQ processor on the upper left, the XC7VX690T FPGA center, 3 Avago CXP TX/RX links (not populated) and 4 Avago MiniPODs on the bottom. Power modules are black. There are connections for JTAG, QDR RAM, a Module Management Controller, and MicroSD slot on the back.

Fig. 5. Top: A diagram of the trigger indicating the connections needed for an upgrade of the calorimeter trigger in parallel to the existing trigger, including the conversion to optical outputs. Bottom: In addition to the oRSC, two mezzanine boards, the oSLB (left) for optical conversion and duplication of ECAL TPs and the oRM (right), preserve the function of the legacy trigger while commissioning the upgrade.

The connections necessary for an upgrade of the calorimeter trigger in 2015 and 2016, installed in parallel to the existing trigger, are shown in the top of Fig. 5. Two more custom boards were built to replace copper links. The oSLB (optical Serial Link Board) duplicates ECAL TPs from the existing ECAL back-end. The oRM (optical Receiver Mezzanine) was necessary to keep the present trigger

functional while commissioning both stages. They are shown in the lower half of Fig. 5.

IV. STAGE-1 (2015)

Since the 2016 upgrade would not be available until all the back-end upgrades were fully installed and commissioned, the decision was made to install an intermediate upgrade of the calorimeter trigger to improve the performance of the calorimeter trigger for p-p and heavy-ion with only a modest investment. For this eighteen 9U oRSCs were installed in a spare VME slot in the 18 RCT crates and cabled up to the 80 MHz RCT parallel output. One MPO-12 per oRSC was connected to the legacy trigger and operated at 2 Gbps to preserve the existing RCT-GCT connection, and 3 x 2 fibers per oRSC were connected to two MP7s (one for p-p and one for heavy-ion) and a CTP7 for readout.

Fig. 6. From top left, counter-clockwise: The stage-1 MP7 crate for triggering during 2015. The CTP7 crate for readout of the RCT data, and the RCT racks with the oRSCs, their cables, and fibers.

Commissioning the Stage-1 Calorimeter Trigger in parallel would ensure when the switchover was made that it would perform as expected. Fortunately, the CMS Global Trigger (GT) has a spare crate available in the CMS electronics cavern, with its own separate connection to CMS central DAQ. The output of the MP7 for the Stage-1 p-p was connected to this spare GT crate so it could be read out at the same time as the RCT-GCT chain connected to the main crate which provided physics triggers for CMS. In this way, Stage-1 could be timed in and monitored without disturbing p-p data taking. Examples of the online monitoring developed, including hardware (Fig. 7) and data-quality (Fig. 8) are shown.

As soon as the operation, including configuration, monitoring, and performance online and offline were validated, CMS switched to triggering with Stage-1. This coincided with the start of the 25ns LHC p-p operations in August 2015. To allow for further monitoring in case of unforeseen problems, the GCT was connected to the GT test crate and was disconnected a few months later.

The Stage-1 has been part of CMS data taking for several months and performance has been monitored and studied in

detail. The electron/photon trigger efficiency is remaining high even when isolation is imposed to reduce the trigger rate, and the new tau trigger, using a 2x1 region object instead of a 3x3 regions has improved its performance significantly. The results can be seen in Fig. 10. The jet algorithm uses 12x12 (3x3 RCT regions) and is working as expected, and data shows perfect agreement with the emulated performance (Fig. 11). More details can be found in [9], [10].

Fig. 7. First-level online hardware monitoring for the Stage-1 MP7, showing the status of the 10 Gbps links as well as clocks. More details are on other panels accessible via hyperlinks from this panel.

Fig. 8. A screenshot of the CMS online Data Quality Monitoring (DQM) display. It uses the CTP7 readout of the RCT to monitor the RCT performance in nearly real-time. Bit level comparisons are made of output data versus the expected result emulated with the input trigger primitives. This makes very small discrepancies easy to spot. For example, the orange block in the plot on the middle right was due to bit errors on a single card in the system.

V. STAGE-2 (2016)

For the second-stage of the calorimeter trigger upgrade, there were two architecture choices proposed, a conventional pipelined or time-multiplexed. The hardware is capable of implementing either choice, and the final decision was to implement the time-multiplexed version. In this version, the Layer-1 cards, the CTP7s, receive the trigger towers from regions of the HCAL, ECAL, and HF. Each card then sends these towers for different bunch crossings on different fibers to each of 9 Layer-2 cards, the MP7s, resulting in all

calorimeter data for one BX arriving at one FPGA for processing, for very high granularity trigger algorithms. Layer-2 has the flexibility to be reconfigured to provide additional FPGA resources for the Layer-2 algorithms or to handle more data from Layer-1, such as in a scenario where the size of trigger towers goes from 16 to 24 bits on the optical fibers. A block diagram of the time-multiplexed calorimeter trigger is shown Fig. 11.

Fig. 9. Left: Stage-1 electron/photon (e/γ) trigger efficiency versus reconstructed p_T for different e/γ trigger and thresholds. Isolation reduces the rate significantly with only a small drop in efficiency. Right: Tau trigger efficiency for 2 Stage-1 upgrade triggers and the legacy system. A tremendous improvement in the tau trigger was realized with the Stage-1 hardware.

Fig. 10. Comparison of Stage-1 trigger output to emulated output data using input. Perfect agreement is observed, left is the p_T of the central jets, and right is the pseudorapidity (η).

Fig. 11. A block diagram of the time-multiplexed trigger. The top Layer-1 cards (CTP7s) will each send trigger primitive data to every Layer-2 card (MP7) as well as several redundant nodes.

Installation of the Stage-2 (2016) calorimeter trigger is complete. The first steps involved conversion of the calorimeter back-end (BE) hardware to send trigger primitives on optical fiber.

ECAL accomplished this by replacing the copper Serial Link Board with an optical oSLB (Fig. 5) with two outputs at 4.8 Gbps. One output is sent to the legacy Regional Calorimeter Trigger that replaced ECAL input receiver mezzanines with the oRM (Fig. 5) to preserve the ECAL-RCT link and enable the upgrade's installation in parallel while operating the RCT-GCT and then the Stage-1 Calorimeter Trigger.

The forward calorimeter (HF) completely replaced its back-end with a μ TCA system consisting of 3 crates of 12 μ TCA HCAL Trigger and Readout (μ HTR) cards each covering $|\eta| < 5$. It sends trigger primitives to the RCT at 4.8 Gbps that are received with an oRM to preserve the legacy system and to the Stage-2 Layer-1 CTP7s at 6.4 Gbps with improved HF tower granularity.

To upgrade the HCAL (barrel and endcap, $|\eta| < 3$) the decision was made to split the fiber input to the back-end so that the 9 crates of μ HTRs could be installed in parallel to the existing system as it ran through 2015. This preserved the original copper links to the RCT while the new fiber connections were made to the patch panels to the CTP7s. All back-end conversions are now complete and the connections have been tested.

Fig. 12. Top-left: The ECAL back-end TCC crates with oSLBs installed. Two blue fibers per oSLB connect to the RCT oRMs and to Layer-1 patch panels, top-right photo, the orange fibers are HCAL and HF, and in the lower picture is a crate of μ TCA HCAL Trigger and Readout (μ HTRs) cards, the new back-end for this CMS subdetector.

Eighteen 1U patch panels were installed in the back of the rack of the CTP7s for Layer-1 to receive the ECAL, HCAL, and HF trigger primitives. In total, 1152 LC connectors were

mapped onto 108 MPO-12 connections. Photographs of the back-ends and the patch panels can be seen in Fig. 12.

Via the Layer-1 patch panels described previously, 18 Layer-1 CTP7s receive their input trigger primitives (TPs) from the calorimeter back-ends. These in turn send multiple copies of the TPs to each Layer-2 MP7 via another custom patch panel. This patch panel uses a custom Molex FlexPlane to route the fibers to the MP7s. This reduces the footprint of the panels from an entire rack to only 6U. The MP7s in turn perform the trigger algorithms and forward the results to the de-multiplexer before it is sent to the new μ TCA Global Trigger for final selection.

Fig. 13. Clockwise from Top-left: The Stage-2 Layer-1 CTP7 rack with connections from the Layer-1 Patch Panels (Fig. 12). The output goes to the Layer-2 Patch Panels (top-right), which uses Molex FlexPlane (middle-right) to route the connections to the Stage-2 Layer-1 MP7 crate (bottom).

The goal of parallel data taking with Stage-2 is to demonstrate readiness for the 2016 data taking, the same as was done for Stage-1. It is possible to connect the output of the chain to the Global Trigger's test crate or to the new μ TCA based Global Trigger [11]. The μ TCA based Global Trigger presently is in the final stages of commissioning and nearly ready for the parallel running.

Stage 2 optical links have been validated and data transfers have confirmed the correct mapping at each layer. Patterns have been sent from Layer-1 and internally to validate algorithms. An example of this for the e/γ algorithm is seen in Fig. 14.

VI. SUMMARY

The upgrade CMS calorimeter trigger upgrade hardware is completely installed, and in August 2015 the stage-1 trigger became the primary calorimeter trigger for CMS. This installation allowed us to keep our physics trigger thresholds

low enough for CMS to avoid losing valuable data in 2015. The stage-2 upgrade has been installed in parallel in 2015 and is currently in the commissioning phase, set to begin operation by 2016. In order to facilitate this, a number of hardware upgrades or changes have already been made to the calorimeter back-end to duplicate the data, yet keep the original trigger functionality. With these upgrades, the CMS calorimeter trigger will retain good acceptance for electroweak physics, TeV scale searches, and heavy ion physics.

Fig. 14. Comparison of the Stage-2 e/γ algorithm as implemented in the hardware and in the software emulation showing excellent agreement.

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