The Compact Muon Solenoid Experiment

Conference Report

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Installation and Commissioning of the CMS Level-1 Calorimeter Trigger Upgrade

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Abstract

The Compact Muon Solenoid (CMS) experiment is currently installing upgrades to their Calorimeter Trigger for LHC Run 2 to ensure that the trigger thresholds can stay low, and physics data collection will not be compromised. The electronics will be upgraded in two stages. Stage-1 for 2015 will upgrade some electronics and links from copper to optical in the existing calorimeter trigger so that the algorithms can be improved and we do not lose valuable data before stage-2 can be fully installed by 2016. Stage-2 will fully replace the calorimeter trigger at CMS with a micro-TCA and optical link system. It requires that the updates to the calorimeter back-ends, the source of the trigger primitives, be completed. The new 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, and installation of stage-1 in 2015 will be described, as well as the integration and parallel installation of the stage-2 in 2015, for a fully upgraded CMS calorimeter trigger in operation by 2016. Solenoid (CMS) experiment is currently installing an upgrade to their Calorimeter Trigger to ensure that the trigger thresholds can stay low, and physics data collection will not be compromised by these challenging conditions. The electronics will be upgraded in two stages. Stage-1 will upgrade some electronics and links from copper to optical in the existing calorimeter trigger so that the algorithms can be improved and we do not lose valuable data before Stage-2 can be fully installed. Stage-2 will fully replace the calorimeter trigger at CMS with a micro-TCA and optical link system, and require that the updates to the calorimeter back-ends, the source of the trigger primitives, are completed. The new 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, and installation of stage-1 in 2015 will be described, as well as the integration and parallel installation of the stage-2 in 2015, for an fully upgraded CMS calorimeter trigger in operation by 2016.

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I. INTRODUCTION

In early 2015, the Large Hadron Collider (LHC) at CERN will restart with the Run 2 physics program. The repairs made to the magnet interconnections during Long Shutdown 1 (LS1) will allow the LHC to increase its center-of-mass energy from 8 to 13 TeV. The luminosity will also increase and the number of interactions per crossing could be greater than a factor of 2 compared to 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 physics events more challenging.

The original specification for the Compact Muon Solenoid (CMS) experiment was a maximum level-1 trigger rate of 100 kHz [1]. To exceed this, some detector systems (e.g. tracker) would have to undergo major upgrades. Instead, CMS will upgrade its trigger hardware and use more sophisticated algorithms to keep events that would be lost if thresholds were increased 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 Figure 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 PRESENT AND FUTURE CMS CALORIMETER TRIGGER

The current CMS calorimeter trigger is built entirely of custom electronics. It is built in two stages, a Regional Calorimeter Trigger (RCT) [2] and a Global Calorimeter Trigger (GCT) [3]. The RCT comprises 18 crates for receiving Trigger Primitives (TPs) in the form of an 8-bit transverse energy (E_T) and quality bit from the over 8000 towers in the Hadronic, Forward, and Electromagnetic Calorimeters (HCAL, HF, and ECAL). It processes this information in parallel and sends 18×8 e/γ candidates' E_T (1×2

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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 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).

The calorimeter trigger upgrade [4,5,6] will be performed in two stages. Stage-1 will use the existing RCT and replace the GCT with a second level consisting of custom μ TCA hardware. A 9U optical Regional Summary Card (oRSC) (Fig. 2) will be added to the RCT crates to transmit data optically to the new hardware, while preserving 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 regional sums, repurposed 2x1 tower sums for tau and e/γ finding, and quality bits from the RCT and sends them on two optical links at 10 Gbps to the 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 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 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 and legacy trigger operation.

Stage-2 will be installed in parallel to the stage-1 and is scheduled to be ready for physics at the beginning of 2016. Before it is installed there must be upgrades to optical outputs of the HCAL, HF, and ECAL back-end electronics before it can be fully functional. Instead of the present conventional pipelined trigger, stage-2 will use a new architecture with time multiplexing. For this, thirty-six CTP7s will receive TPs at speeds of up to 6.4 Gbps from the calorimeters, time-order and send copies at 10 Gbps to up to 12 different MP7s that work on one LHC crossing at a time, scanning the entire calorimeter by rows of towers and finding trigger object candidates. The results are sorted, either in the main processor, or in a final demultiplexing stage before being sent to the Global Trigger.

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 Figure 5. Two of the mezzanines, the oSLB (optical Serial Link Board), to duplicate ECAL TPs and oRM (optical Receiver Mezzanine), necessary to keep the present trigger functional while commissioning both stages, are shown in the lower half of Figure 5.

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), firmware via MicroSD card or conventional PROM.

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 CXP TX/RX links (not populated) and 4 MiniPODs on the bottom. Power modules are black. There is a Module Management Controller, connections for JTAG, QDR RAM, and MicroSD (back).

Fig. 5. A block diagram of the trigger showing the connections necessary for an upgrade of the calorimeter trigger in parallel to the existing trigger, including the conversion to optical outputs. Two new mezzanine boards, the oSLB for optical conversion and duplication of ECAL TPs and the oRM, preserve the function of the legacy trigger while commissioning the upgrade.

III. TESTING AND INTEGRATION

Tests have been completed to validate the time-multiplexed trigger (TMT) concept, and another TMT demonstrator with production boards was successful in September 2013. Integration tests between prototype systems validated the different link speeds and connectivity before production began. The recent focus of the upgrade tests was on the integration of the new hardware and validation of the data transmission through the trigger hardware chain.

A. Stage-1

In April 2014, a scaled down version of the stage-1 trigger was created for integration tests. Two RCT crates had an oRSC installed, and all of the 23 output links on each oRSC card operated at 10 Gbps and was connected to a patch panel that fed a MP7 and a CTP7. Thirty-six of these links sent data to the MP7 (the same number of links as in the production system), and 10 links sent data to a CTP7 for validation. A long-term, 48-hour test was performed between the RCT and oRSCs, with no errors observed. A separate IBERT test of the oRSC to the MP7 at 10 Gbps achieved a bit error rate of less than 10^{-18} . Pattern data were then played back from the oRSC to the MP7 and the CTP7 and checked, with no errors observed. A diagram of the test setup and a resulting eye diagram can be seen in Figures 6 and 7.

Fig. 6. Stage-1 test setup: Test patterns were programmed into the RCT and sent at 10 Gbps from the oRSC to the MP7 and CTP7.

Fig. 7. Xilinx IBERT Eye diagram obtained at the MP7 during the stage-1 tests, showing good quality transmission at 10 Gbps.

B. Stage-2

In July and August 2014, a scaled down version of the stage-2 trigger was assembled and tested. For this test, 16 links of 8 ECAL oSLBs on an ECAL backend Trigger Concentrator Card (TCC) and 16 HCAL μ HTR links were connected to a CTP7 via a patch panel. This CTP7's output was connected via two patch panels to a MP7 (see Figure 8 for a diagram of the test setup). A battery of tests was performed and all tests were successful.

Data was captured and aligned from the oSLBs at 4.8 Gbps and the μ HTRs at 6.4 Gbps at the CTP7. The CTP7 simulated time-multiplexed data at 10 Gbps and it was captured with the

MP7. Finally, data was propagated from the ECAL TCC and μ HTR, sent to the CTP7 at 4.8 and 6.4 Gbps respectively, sent out at 10 Gbps to the MP7 and captured. The data captured was validated offline with an emulated version of the system and agreement was perfect, as shown in Figure 9.

Fig. 8. Stage 2 Test setup, ECAL TCC with oSLBs and upgrade HCAL μ HTR back-end providing data to the Layer-1 CTP7 at 4.8 and 6.4 Gbps. Data was aligned, time-multiplexed, and sent at 10 Gbps to the layer-2 MP7 and captured.

Fig. 9. Comparison of captured stage-2 test data simulating Jets with emulated. The firmware result is a line and the emulator result is a dot. Perfect agreement was seen for all Jet E_T .

IV. INSTALLATION AND COMMISSIONING

A. Stage-1

The hardware of stage-1 is already installed in the CMS electronics cavern and commissioning is beginning. Eighteen oRSCs have been installed in the existing 18 RCT crates and connected to the RCT output. The fibers have been routed and are connected to GCT (for legacy operation) and stage-1 patch panels, sent to both the MP7 for triggering and the CTP7 for readout. The software for operation is in use and the development of hardware monitoring is in progress.

Testing is currently underway to validate all the connections with the near term goal of restoring the legacy trigger via the connection of the oRSC to the GCT. At the same time, the connections to the MP7 for triggering and the CTP7 for readout are being validated. Initial tests will use the connection to the μ TCA crate controller to read out the data, and the connection to CMS Data Acquisition (DAQ) will need to be established before the data monitoring can be centralized. Operation of the stage-1 will begin in parallel to the legacy system with the aim of making the switch from legacy to stage-1 as soon as it is fully commissioned in early 2015. Photographs of the stage-1 hardware installation are shown in Figure 10.

B. Stage-2

Even with all the activity for stage-1, a number of components have already been installed for the stage-2, Time-Multiplexed Trigger. Most of these will allow duplication of data in a way that allows operation of stage-1 while stage-2 of

the calorimeter trigger upgrade is commissioned. The ECAL has completed installation of all the fibers and the oSLBs on all of its TCCs. The HF has nearly finished conversion of its back-end to the optical μ TCA μ HTR. For the remaining conversion of HCAL, the back end input fibers for the barrel and endcap have been split so that the conversion to μ HTR can take place at the same time as physics data taking in 2015. All of the patch panels are now in place to receive all of the trigger primitive data from the calorimeters on fibers and propagate the time-multiplexed data from the CTP7s to the MP7s. MP7s are already in place as well as several CTP7s for integration work. The full complement of CTP7s should arrive in early 2015. Some photos of the installation can be seen in Figure 11.

Fig. 10. 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.

Fig. 11. From the left, clockwise: The ECAL back-end oSLBs installed (light blue fibers). The HF μ HTR crate for parallel commissioning. A μ TCA crate populated with MP7s for Layer-2 of the stage-2 trigger

V. SUMMARY

The stage-1 CMS calorimeter trigger upgrade hardware is completely installed. The commissioning phase has now begun in earnest. This installation will allow us to keep our physics trigger thresholds low enough so CMS avoid losing valuable data in 2015. The stage-2 upgrade will be installed in parallel in 2015, in order 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 its sensitivity to electroweak physics, TeV scale searches and heavy ion physics.

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