Integration of the CMS Regional Calorimeter Trigger Hardware into the CMS Level-1 Trigger

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Abstract

The electronics for the Regional Calorimeter Trigger (RCT) of the Compact Muon Solenoid Experiment (CMS) have been produced and tested. The RCT hardware consists of 18 double-sided crates containing custom boards, ASICs, and backplanes. The RCT receives 8-bit energies and a data quality bit from the HCAL and ECAL Trigger Primitive Generators (TPGs) and sends it to the CMS Global Calorimeter Trigger (GCT) after processing.

Before installation, integration tests were performed. Data was successfully received from the TPG electronics and read out with a RCT Jet Capture Card. These tests, other tests involving more trigger subsystems, their results, and the RCT installation will be described.

I. Introduction

The Compact Muon Solenoid (CMS) is a general-purpose detector that will operate at the Large Hadron Collider (LHC). Its construction is currently underway at the European Laboratory for Particle Physics (CERN) near Geneva, Switzerland. This large detector will be sensitive to a wide range of new physics at the high proton-proton center of mass energy $\sqrt{s}$ =14 TeV [1].

At the LHC design luminosity of 10^{34} cm^{-2} s^{-1}, a beam crossing every 25 ns contains on average 17.3 events. These 10^9 interactions per second must be reduced by a factor of 10^7 to 100 Hz, the maximum rate that can be archived by the on-line computer farm. This will be done in two steps. The level-1 trigger first reduces the rate to 75 kHz, and then a High Level Trigger (HLT), using an on-line computer farm, handles the remaining rate reduction.

The CMS level-1 electron/photon, τ-lepton, jet, and missing transverse energy trigger decisions are based on input from the level-1 Regional Calorimeter Trigger (RCT) [2]. The RCT plays an integral role in the reduction of the proton-proton interaction rate (10^9 Hz) to the High Level Trigger input rate (10^5 Hz) while separating physics signals from background with high efficiency. The RCT receives input from the brass and scintillator CMS hadron calorimeter (HCAL) and $PbWO_4$ crystal electromagnetic calorimeter (ECAL), that extend to $|\eta|$=3 (pseudorapidity η is $-\ln(\tan(\theta/2)$ where the x-y plane is perpendicular to the beam line defined by z). An additional hadron calorimeter in the very forward region (HF) extends coverage to $|\eta|$=5. A calorimeter trigger tower is defined as 5x5 crystals in the ECAL of dimensions 0.087x0.087 ($\Delta\phi$x$\Delta\eta$), which corresponds 1:1 to the physical tower size of the HCAL.

II. RCT Hardware

A. *Primary RCT Cards*

The RCT electronics comprises 18 crates for the barrel, endcap, and forward calorimeters, and another crate for clock distribution. These will be housed in the CMS underground counting room adjacent to and shielded from the underground experimental area.

Twenty-four bits comprising two 8-bit calorimeter energies, two energy characterization bits, a LHC bunch crossing bit, and 5 bits of error detection code will be sent from the ECAL, HCAL, and HF calorimeter electronics to the nearby RCT racks on 1.2 Gbaud copper links. This is done using one of the four 24-bit channels of the Vitesse 7216-1 serial transceiver chip on calorimeter output and RCT input, for 8 channels of calorimeter data per chip. The RCT V7216-1 chips are mounted on mezzanine cards, located on each of 7 Receiver Cards and the single Jet/Summary Card for all 18 RCT crates. The eight mezzanine cards on the Receiver Cards are for the HCAL and ECAL data and the one mezzanine card located on the Jet/Summary Card is for receiving the HF data. The V7216-1 converts serial data to 120 MHz TTL parallel data, which is then deskewed, linearized, and summed before transmission on a 160 MHz ECL custom backplane to 7 Electron Isolation Cards and one Jet/Summary Card. The Jet/Summary Card receives the HF data and sends the regional E_T sums and the electron candidates to the Global Calorimeter Trigger (GCT). The GCT implements the jet algorithms and forwards the 12 jets to the Global Trigger (GT).

The Receiver Card (shown in Figure 1), in addition to receiving calorimeter data on copper cables using the V7216-1, shares data on cables between RCT crates. Synchronization of all data is done with the local clock and the Phase ASIC (Application-Specific Integrated Circuit--described below). The Phase ASIC also checks for data transmission errors. Lookup tables are used to translate the incoming E_T values onto several scales and set bits for electron identification. Adder blocks begin the energy summation tree, reducing the data sent to the 160 MHz backplane.

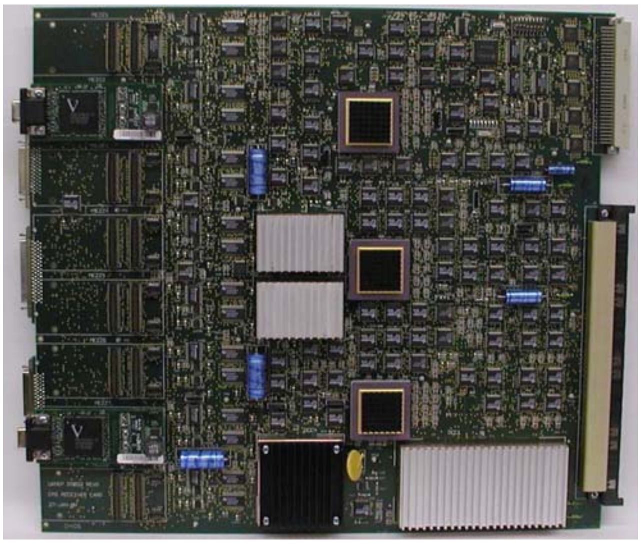

Figure 1: Front of a Receiver Card showing two Receiver Mezzanine Cards in place and Adder ASICs.

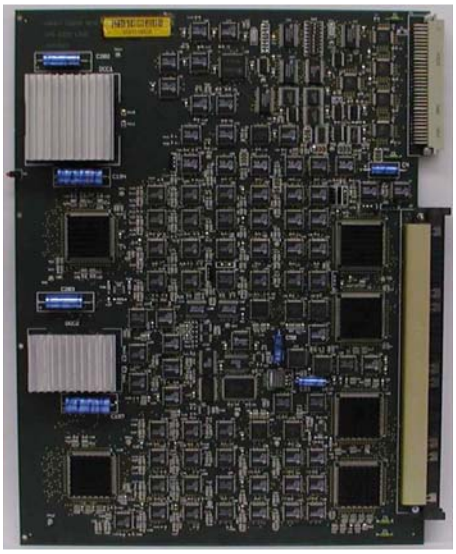

Figure 2: Electron Identification Card showing Sort ASICs and EISO ASICs.

The Electron Isolation Card (shown in Figure 2) receives data for 32 central towers and 28 neighboring towers via the backplane. The electron isolation algorithm is implemented in the Electron Isolation ASIC described below. Four electron candidates are transmitted via the backplane to the Jet/Summary (J/S) Card. The electrons are sorted in a Sort ASIC on the J/S Card and the top 4 of each type are transmitted to the GCT for further processing. The J/S Card also receives E_T sums via the backplane, and forwards them and two types of muon identification bits (minimum ionizing and quiet bits – described later) to the GCT. A block diagram of this dataflow is shown in Fig. 3.

To implement the algorithms described above, five high-speed custom Vitesse ASICs were designed and manufactured, a Phase ASIC, an Adder ASIC, a Boundary Scan ASIC, a Sort ASIC, and an Electron Isolation ASIC [3]. They were produced in Vitesse FX™ and GLX™ gate arrays utilizing their sub-micron high integration Gallium Arsenide MESFET technology. Except for the 120 MHz TTL input of the Phase ASIC, all ASIC I/O is 160 MHz ECL.

The Phase ASICs on the Receiver Card align and synchronize the data received on four channels of parallel data from the Vitesse 7216. The Adder ASICs sum up eight 11-bit energies (including the sign) in 25 ns, while providing bits for overflows. The Boundary Scan ASIC handles board level boundary scan functions and drivers for data sharing. Four 7-bit electromagnetic energies, a veto bit, and nearest-neighbor energies are handled every 6.25 ns by the Electron Isolation ASICs, which are located on the Electron Isolation Card. Sort ASICs are located on the Electron Isolation Card, where they are used as receivers, and are located on the J/S Cards for sorting the e/γ. All these ASICs have been successfully tested on the boards described below, and procured on in the full quantities needed for the system. The boards described have been produced using these ASICs and sufficient quantity has been obtained to fill 18 crates and create a stock of spares.

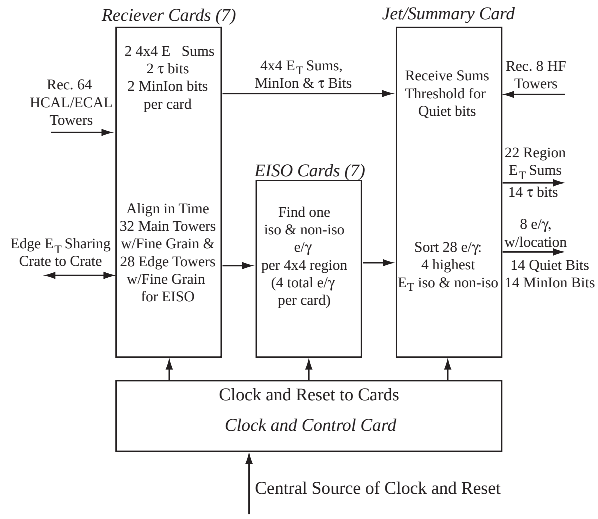

Figure 3: Dataflow diagram for the crate, showing data received and transferred between cards on the 160 MHz differential ECL backplane. Brief explanations of the card functionality are shown. For more details see the text or reference [2].

Currently in production is the Master Clock and Control Crate and cards. This crate will be centrally located among the 18 RCT crates and provide clock and control signal distribution. It includes a Clock Input Card (CIC), to receive the LHC clock, Bunch Crossing Zero (BC0), and CMS local control signals via an optical fiber to a LHC TTCrm mezzanine board [4], and to set the global alignment of the signals. This CIC will feed fan-out cards that will distribute the signals to the individual crates via low-skew cable. Delays on these cards will allow fine-tuning of the signals to the individual crates.

B. RCT Test Cards

For validation and production testing, two special test boards were developed to verify the input and output of the RCT. Versatility was built into the cards so that they may be used by other groups and in other situations at CMS.

The Serial Test Card (STC) was the first of these cards to be produced. It can be used in two ways. It can transmit data that mimics the input from the calorimeter Trigger Primitive Generators (TPGs). In this configuration they were used to validate the RCT Receiver Card links. Several cards were daisy chained together to produce 4 inputs to a RC. With this setup, all of the RC links and routes that could not be validated without active links were tested in a reasonable amount of time.

The STC can also be configured to receive data from an active link. A pair of cards, a transmitting card and a receiving card, was used to validate all the Receiver Mezzanine Cards. Additionally, the receive mode was used to validate the link board for the TPGs, the Serial Link Board (SLB), in another test stand.

The second test card, the Jet Capture Card (JCC) was developed to capture the output of the JSC in a variety of modes and if needed, generate an external trigger. It sits in the spare VME slot of an RCT crate, receives clocks and control signals from the CCC on two low-skew cables and data on six 68-pin cables from the JSC. Using the ability of the RCT to repeatedly cycle through its LUTs, it was possible to validate the data paths of a full RCT crate with changing patterns for an extended period of time. The capture feature was also used in integration tests described later in and the trigger feature will be exploited in the CMS Magnet Test and Cosmic Challenge (see below) [5].

III. INTEGRATION

A. Trigger Primitive Generators

The HCAL Trigger Readout (HTR) Boards and the ECAL Trigger Concentrator Cards (TCCs) provide the input to the RCT using a Serial Link Board (SLB), a mezzanine with the V2716-1 mounted on each type of card. The SLB is configurable, with two Altera Cyclone® FPGAs for data synchronization at the V2716-1, Hamming code calculation, FIFOs, and histogramming. The clocking for the SLB is separate from the HTR and TCC primary clocking to ensure alignment at the RCT. The HTR can have up to 6 SLBs and receives data from the front end on fibers into its front panel. The TCC has up to 9 SLBs and also receives front-end data via a fiber to its front panel.

B. Early Integration Tests

Before a CMS electronics integration facility was ready for use at CERN, integration had already begun at UW and at CERN. A single input cable was used, and the output and errors monitored with an oscilloscope for short runs to verify the designs and firmware of the HCAL Trigger Readout (HTR) boards, SLBs, and the RCT Receiver Card. These tests also evaluated a couple of new types of cable for the links, one of which proved to be the final choice for the system (Kerpen MegaLine® 8 [6]).

C. CMS Electronics Integration Facility

While the underground counting room was being readied, there was a pressing need for laboratory space to perform integration of electronics subsystems. For this an aboveground facility was built in an existing space at CERN. This facility has separate lab spaces with cable trays in-between and a row of racks outside of the labs identical to what exists underground at CMS, so ample space is available to integrate multiple trigger subsystems at the same time. The Regional Calorimeter Trigger was one of the first residents.

1) ECAL and HCAL TPGs

Initial tests with the HCAL HTR and ECAL TCC (Trigger Concentrator Card) were performed separately in the integration facility. Only a few cables were needed for initial tests of the input to the RCT so tests were done between the labs in the facility. Simple pattern data was sent from the HTR and TCC and the Jet Capture Card was used to verify transmission and alignment through the RCT. The RCT received all of this data on its HCAL input links, and used the functionality of the LookUp Tables (LUTs) and Adder ASICs on the Receiver Cards as a transparent way of reading out the results using the JCC attached to the JSC. The values of these regional sums were read out and the alignment of the data checked. Common clocking was done via a TTCvi (Trigger Timing and Control VME interface module) [4] located in the HCAL crate. Alignment of up to 6 links simultaneously was obtained and monitored for hours at a time.

After these successful tests, integration was moved to the integration row of the facility (See Figure 4 and Figure 5). This allowed ECAL and HCAL to send data simultaneously to the RCT, and use a clocking system with the same hardware as the CMS clocking system, the LTC (Local Trigger Control) [7] and 3 TTCci modules (CMS Trigger Timing and Control module) [7], one for each subsystem, the ECAL, HCAL, and RCT/SLB.

Figure 4: Front of the HCAL (right), ECAL (center), and RCT (left) racks at the integration facility. The top crate of the HCAL has the 19 cables attached to SLBs mounted on HTR cards. The ECAL rack has the TCC with SLBs and cables. The RCT has 6 cables (black) from the JSC to the JCC, and two cables (beige) from the CCC to the JCC.

One crate of HCAL HTRs sent data on 19 cables, and one ECAL TCC sent data on 9 additional cables (Figure 5). In this way, the links were run for extended periods of time and debugging of intermittent problems became possible. After long-term stability tests proved successful, this setup was also used for firmware evaluation, software development, and continuing integration work.

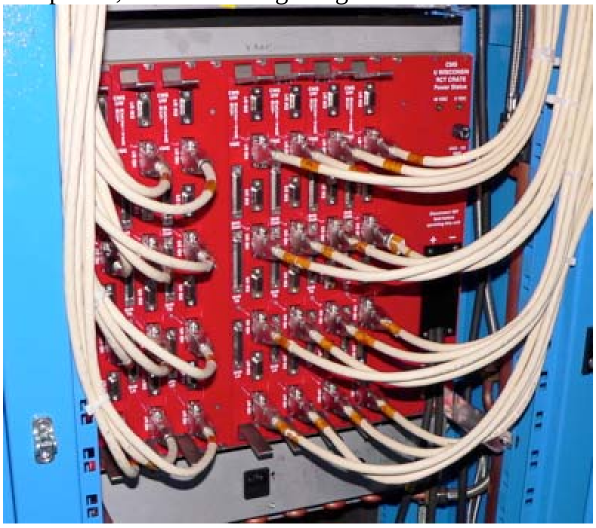

Figure 5: Rear of the RCT rack showing the 28 cables as input to 7 Receiver Cards. Half of the links were used.

2) Global Calorimeter Trigger

On its own, the RCT is able to generate the equivalent of 64 LHC bunch crossings of pattern data by cycling addresses of its Receiver Card LUTs. This functionality was used to test the interface with the Global Calorimeter Trigger (GCT), the Source Card. In its final form, the GCT will receive the differential ECL output of the 18 RCT JSCs. In total 66 Source Cards will receive 108 68-pin cables with regional sums, e/γ candidates, muon and τ bits and use this data to find jets, calculate global quantities, and find the four highest energy e/γ candidates of each type, isolated and non-isolated.

Long-term tests were performed successfully using two RCT crates synchronized with each other. The synchronization was achieved using a prototype RCT Master Clock Crate and Clock Input Card and a single TTCci with optical fan-out as the clock source for both the RCT and the GCT.

3) Preparations for the Magnet Test and Cosmic Challenge

In summer and autumn 2006 the CMS barrel rings and endcap disks, along with parts of the muon system, ECAL, HCAL, and tracker were used to understand the magnetic field and perform a "slice test" of the CMS DAQ system. The Magnet Test and Cosmic Challenge (MTCC) included the trigger systems. In order for the RCT to be used as part of the trigger in the second phase (autumn) of the MTCC, it was necessary to use the Jet Capture Card's capability of sending a trigger out. This required testing with two different systems.

One, the Global Trigger, would receive two trigger signals at its Pipeline Synchronization Board (PSB) and perform logic on the board using its FPGAs. For this, synchronization with orbit structure of the LHC was required. Therefore, the RCT used the pattern generation capability of the ECAL TCC to send predictable data via its links, which was used to create up to 2048 four-bit JCC trigger patterns for every LHC orbit. The patterns were provided to the Global Trigger, and they were able to verify that the data was coming over the link.

The other, the LTC, part of the CMS TTC system, can receive LVDS inputs and record them as part of its readout. Again, the ECAL was used as input and a JCC trigger signal out was sent to the LTC once per orbit. The rate, determined by the LTC software, was matched to BC0 rate, and was identical, so the test was determined a success.

4) Future Tests at the Integration Facility

Currently in the planning stage is a long-term test to study the software trigger emulators and test the algorithms of the RCT. The RCT LUTs can be programmed to duplicate incoming data. This will be set up and the RCT trigger emulator will be used to predict the outputs of the RCT. The HTR emulator will also be tested, and all of this will be done using a CMS software package for trigger control, the Trigger Supervisor [8]. This test will be done using two RCT crates and two JCCs and take place in October.

D. HCAL TPG to RCT in MTCC

As part of the second phase of CMS Magnet Test and Cosmic Challenge, the RCT has installed a crate and all support in the counting house for the MTCC. Data comes from the HCAL barrel HTRs (Figure 7) and 56 links are connected at the rear of the RCT crate (Figure 8). The desired trigger is a coincidence between the HCAL top barrel and HCAL bottom barrel. In order to separate these paths, the cables from the HCAL top goes to the HCAL inputs of the RCT, and the HCAL bottom cables go to the ECAL input of the RCT. A special LUT configuration allows the paths to remain separate, and produces two separate ORs performed by the RCT with its JCC. These two signals come out of the JCC and either go to the LTC via small logic board to perform an AND of the two signals, or directly to the GCT PSB, where the AND is performed internally.

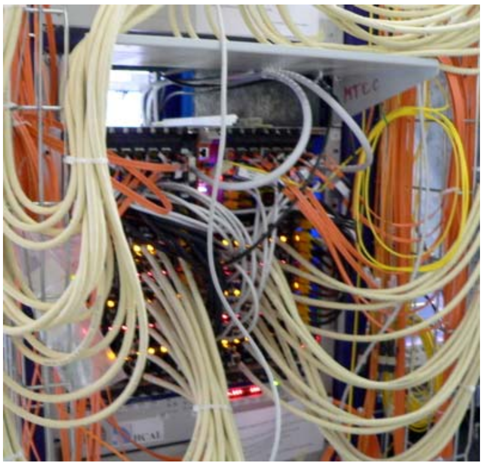

Figure 6: Cables to the RCT (beige) from the crate with HCAL HTRs for the bottom of the detector.

Figure 7: Cables into the RCT in the MTCC counting house.

The crate is ready and the links have been checked. The MTCC will restart in early October.

E. Integration Underground at CMS

Many of these tests will be expanded when trigger subsystems move to the underground counting room. As part of the commissioning process, it will be necessary to verify if all of the 1026 links to the RCT are attached, their (correct) location, and their long-term stability. In addition, after any board swaps or repairs, software tools are needed to recheck the connections. It is also expected that between LHC fills, tests will be run to help diagnose and find any problems that developed during running.

IV. COMMISSIONING

A. Commissioning Underground at CMS

Installation has begun underground at CMS. The RCT has been allocated 10 racks that will hold a total of 21 RCT crates, 6 Global Calorimeter Crates, and a Clock crate for the HCAL. Nineteen of the RCT crates will be used as part of the final system. This includes a Master Clock Crate and eighteen of the 20 standard RCT crates. Two of the RCT crates will be used for local testing and powered storage.

1) Rack Infrastructure Installation

In late July, as soon as the underground counting room was deemed "ready for crates" a team from Wisconsin arrived to install the rack infrastructure and crates without cards. This included the installation of a custom rack monitoring system. This system, at the heart of which is a Rack Monitor Card, monitors the status of the power supplies, fans and crate temperatures. A serial port on the card is attached to a serial-to-ethernet connection. PVSS [9], an object-oriented process visualization and control system, is being used for the software interface to the Rack Monitor Card. This will enable remote monitoring and control of the racks and crates.

2) Card Installation

In October the RCT cards will be installed. Cards are shipped as pre-tested sets (16 different cards to a crate). Before installation in the crates, the cards will be checked out at the electronics integration facility, using the JCC and a crate self-test. This is repeated again in the underground counting room. To expand the scope of these self-tests, a program of sharing tests using the Master Clock Crate, data-sharing cables, and JCC is in development. This will check all of the inter-crate paths over cables and ensure clock distribution to the crates has been done correctly. In addition, the cables from the HTR and TCC SLBs will be installed and the links validated with expanded versions of previous tests above ground.

V. CONCLUSIONS

The integration and testing of the Regional Calorimeter trigger has expanded our understanding of the hardware and the subsystems that we connect to, the HCAL HTR, the ECAL TCC, and the GCT. It has led to improvements in the hardware and the firmware of the subsystems. As integration continues in the MTCC, and during installation underground, lessons learned will help provide a robust RCT for the turn-on of the LHC in 2007.

Figure 8: RCT Racks underground with crates and infrastructure. No boards have been installed yet.

VI. REFERENCES

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