The CMS Level-1 Trigger Barrel Track Finder

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ABSTRACT: The design and performance of the upgraded CMS Level-1 Trigger Barrel Muon Track Finder (BMTF) is presented. Monte Carlo simulation data as well as cosmic ray data from a CMS muon detector slice test have been used to study in detail the performance of the new track finder. The design architecture is based on twelve MP7 cards each of which uses a Xilinx Virtex-7 FPGA and can receive and transmit data at 10 Gbps from 72 input and 72 output fibers. According to the CMS Trigger Upgrade TDR the BMTF receives trigger primitive data which are computed using both RPC and DT data and can receive and transmit data from a number of muon candidates to the upgraded Global Muon Trigger. Results from detailed studies of comparisons between the BMTF algorithm results and the results of a C++ emulator are also presented. The new BMTF will be commissioned for data taking in 2016.

KEYWORDS: Trigger concepts and systems (hardware and software); Trigger algorithms

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1 Introduction

The CMS experiment L1 trigger system selects interesting physics events at a rate of 100 kHz from an input rate of 40 MHz. It is designed to operate up to a luminosity of $10^{34} \text{cm}^{-2} \text{s}^{-1}$. The luminosity will increase to $2 \times 10^{34} \text{cm}^{-2} \text{s}^{-1}$ with the planned LHC phase I upgrade in 2016 and reach $5 \times 10^{34} \text{cm}^{-2} \text{s}^{-1}$ with the LHC phase II upgrade in 2025. The increase of the luminosity requires more rate reduction and higher efficiency. To achieve this, the trigger strategy has been changed from detector oriented to area oriented trigger systems. In the legacy L1 trigger system of CMS, the information from the different systems is brought together late in the trigger chain. The upgraded trigger is moving the redundancy of the three muon detection systems earlier in the design in order to obtain a higher trigger performance with higher efficiency and better rate reduction [1]. The muon trigger system is shown in the figure 1. In the left side is the legacy trigger and in the right side the upgraded. The Legacy trigger system is segmented to detector related track finders. This scheme has the disadvantage that the correlation among different detectors can not be done before the candidates reach the Global Muon Trigger level (GMT). The upgraded strategy (figure 1, right side) divides the muon trigger systems in three CMS geometrical areas. The Barrel, the Endcap and the Overlap. In contrast with the legacy Drift Tube Track Finder (DTTF) which receives information only from the Drift Tubes (DT)s, the new BMTF receives superprimitives constructed by combining DT and RPC data. The TwinMux system, which consists of six uTCA crates with TwinMux processors, processes RPC hit data and DT stub data and combines them to the barrel super-primitive data which are transmitted to the BMTF. Twelve BMTF processors receive the TwinMux data and deliver the three best muon candidates from each one of the twelve wedge with similar resolution, redundancy and trigger rate than the DTTF. The new algorithm has been validated as well as the optical links with the TwinMux and uGMT.
Figure 1. Moun Trigger Overview. At the left part is the legacy muon trigger system and at the right part is the upgraded.

2 BMTF — hardware

The BMTF is replacing the legacy DTTF by changing the VME standard with the more robust and high speed uTCA. The new system implemented in 690 series Virtex-7 FPGAs which cover the resource needs (logic slices, block memories) as well as total I/O bandwidth. BMTF uses 12 Master Processor — Virtex-7 cards (MP7) (figure 2). MP7 processors have been designed at Imperial College [2]. The MP7 is based on the uTCA standard AMC card for the trigger system of the CMS. The MP7s optical interface is instrumented with six Avago MiniPOD transmitters and six Avago MiniPOD receivers. Each MiniPOD device provides 12 optical links running at 10 Gb/s, giving the MP7 a total optical bandwidth of up to 740 Gb/s in each direction. The optical outputs from the MiniPOD devices are transmitted on unruggedized, non-peelable optical ribbons to 48-way MTP connectors (of which only 36 channels are used) mounted on the front-panel. Each MP7 covers

Figure 2. Master Processor — Virtex-7 card (MP7).
the needs of one wedge of the BMTF trigger system, receives the TwinMux data via 30 links and transmits the algorithm results to the uGMT using a single link. The Virtex-7 690 chip of the MP7 provides plenty of unused resources for upgrading the algorithms by adding extra logic blocks and using larger Look Up tables (LUTs).

3 Muon Track Finders

For the beginning of the 2016 run the algorithm of the legacy algorithm of the legacy Drift Tube Track Finder (DTTF) has been implemented in the new MP7 framework of the BMTF. The MP7 offers enough resources which can be used to improve the resolution and the processing time (latency). In contrast to the DTTF which was using eight VME cards (half crate) to run the track finders for one CMS wedge, the BMTF uses one MP7 which covers the 1/12 of one uTCA crate. Figure 3 shows the installed BMTF with the twelve MP7 in two uTCA 4 U crates. At the bottom of the same rack is the optical patch panel which is used by BMTF to receive the inputs from the upgraded sector collector (TwinMux).

3.1 BMTF algorithm overview

The muon barrel architecture groups the muon detectors in 12 wedges. Each wedge has five sectors and each sector four DT stations and three RPC planes. The front-end electronics generate the muon primitives and send the data to the TwinMux. The TwinMux combines DT and RPC data to create better quality candidates (superprimitives) than the primitives of the DT. Then it fanouts the superprimitives to the BMTF and Overlap Muon Track Finder (OMTF). The BMTF trigger receives
the muon superprimitives from the Barrel area of CMS ($\mid \eta \mid$<0.85). The superprimitives data consist of muon stabs, bending angle and 5 quality bits. The BMTF algorithm uses this information to reconstruct muon tracks and calculate the physical parameters which are the transverse momentum ($p_T$), the $\phi$ and $\eta$ angles, the quality of the candidate and the track addresses. The algorithm has three stages [3]:

1. In the first, called the Extrapolator Unit, the track stabs, the bending angle and the quality bits from different DT stations of one sector are combined using LUTs. Each combination extrapolates the muon candidate to the next station and checks whether it is within an acceptable window. The same algorithm is repeated between neighbor sectors.

2. In the second stage, the Track Assembler Unit receives the acceptable extrapolations and reconstructs a track with the corresponding quality bits. The quality bits gives the candidate track class.

3. The Assignment Unit uses LUTs to assign physical parameters to the algorithm outputs ($p_T$, $\phi$, Eta).

Each BMTF processor finds muon tracks that pass through a muon chamber of one sector and might also go to the neighbor sector (left and right of both the current and neighbor wheel). Picture 4 shows an example of a track. The algorithm processor of the wedge number 2 is searching for muon tracks. It uses primitives that come also from wedge 1 and 3. The algorithms run in parallel for all the sectors of one wedge in the same MP7 card. Each one of the twelve processing cards delivers the three best muon candidates to the uGMT. The uGMT does the muon sorting of all the twelve BMTF processors. Also it cancels duplicated muons that were found by different track finders (ghost busting). The uGMT receive muons candidates from the Barrel, Overlap and Endcap Muon Track Finder (EMTF).
3.2 Algorithm validation

The BMTF algorithm has been validated using artificial muon candidates. Raw data with single muons were generated using the CMS Monte Carlo simulation software. The Monte Carlo data were injected to the input buffers of the BMTF hardware and the results were compared with the results from a bit-to-bit emulation of the BMTF in C++. Large statistical samples from Monte Carlo events are used to determine the discrepancies and evaluate if the algorithm works as expected. Pictures 5, 6 and 7 shows the results of \( p_T \), \( \phi \) and in quality bits after comparing 20,000 muon candidates, generated with flat \( p_T \), from 6 GeV up to 1 TeV.

![Figure 5](image)

**Figure 5.** \( p_T \) (MP7) represents the hardware output and the \( p_T \) (EMU) the emulator output.

39 discrepancies found in \( p_T \), 68 in \( \phi \), 196 in quality bit and 245 in the track addresses out of 20,000 events. The result prove that the hardware and the emulator are in good agreement and the algorithm of the DTTF has been successfully implemented to the new BMTF framework. Further investigations are needed to understand and correct the remaining discrepancies which are observed here between the firmware and the bit-to-bit emulator.

![Figure 6](image)

**Figure 6.** \( \phi \) (MP7) represents the hardware output and the \( \phi \) (EMU) the emulator output.
Figure 7. Qual(MP7) represents the hardware output and the Qual(EMU) the emulator output.

The left plot in picture 8 shows that the Pt difference as a function of pT from the emulator is zero, except of a few points, resulting to a very good agreement between the emulator and the MP7 firmware. Also the right plot shows that the Phi difference as a function of Phi coming from the emulator is zero, except very few cases most of which have one Phi deference. The small number of discrepancies shown in both plots are under investigation.

Figure 8. pT and $\phi$ resolutions versus the emulator value.

4 Slice test

During the last months of the 2015 run a slice of the BMTF trigger was successfully operated at CMS P5 and was used to collect data. One BMTF crate has been installed at USC-55 at rack S1D03. Data from 24 minicrates (6 sectors) have been successfully received by the BMTF. The BMTF hardware transmitted correctly the results of the barrel muon track finder to uGMT [4]. During the slice test the input data came from wheels -2 and -1 and sectors 9,10 and 11. The legacy
DTTF run in parallel. The DTTF has one Phi Track Finder (PHTF) for every sector. The trigger rate of the BMTF was compared to the trigger rate of the corresponding PHTF using the monitoring system of the DTTF. The picture 9 shows the technical bit 22 used to monitor the rate of the BMTF under the CMS cosmic run 262548 and was about 10 Hz. Picture 10 shows the trigger rate of the -2, -1, and -0 PHTFs of the DTTF. The PHTF N2 is 6 Hz, the PHTF N1 is 5 Hz and the PHTF N0 is 4 Hz. The sum of the -2 and -1 is about 11 Hz which is a little higher than the BMTF rate. This difference is reasonable since the unlike BMTF, DTTF receive data also from the endcaps of the CMS. This test proves that BMTF triggers with the expected rate. The BMTF is connected to the upgraded trigger control and timing system called Trigger Distribution and Control System (TCDS) from which it receives the LHC clock, commands for running and sends its status. BMTF also transmits to the CMS DAQ system its input and output data which are used for validation. The BMTF group is currently commissioning the rest of BMTF.

5 BMTF online software

The online software controls BMTF system by using state machines implemented in the SWATCH environment [5]. Basic commands (halt, configure, start) have been prepared and command sequences have been added for algorithm tests. Monitoring panels have been added with the SWATCH framework. The online software package also configures the DAQ link interface which sends packets of trigger data to the DAQ every time a L1 Accept is received. Offline, unpacking software makes the data available for analysis.
6 Summary and status

One of the twelve slices of the BMTF has been installed at CMS in order to be tested in real running conditions and to compare the output with the current trigger system, the DTTF. The cabling has been installed and all connections have been validated. The system is under commissioning. BMTF uses the legacy DTTF algorithms. However, the dynamic range of the pT measurement has been extended from 5 to 9 bits. The algorithms have been successfully validated. This system is integrated with the upgraded CMS timing and control system (TCDS) as well as the new DAQ system.

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Figure 10. DTTF trigger rate during the CMS run 262548.