Status and future prospects of the Muon Drift Tubes System of CMS

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ABSTRACT: A key component of the CMS (Compact Muon Solenoid) experiment is its muon system. The tracking and triggering of muons in the central part relies on Drift Tube (DT) chambers. In 2013 and 2014 a number of improvements and upgrades were implemented, in particular concerning the readout and trigger electronics. The increase of luminosity expected by LHC will impose several constraints for rate reduction while maintaining high efficiency in the CMS Level 1 trigger system.

In order to exploit the muon detector redundancy, a new trigger system has been designed. The TwinMux system is the early layer of the muon barrel region that combines the primitives information from different subdetectors: DT, Resistive Plate Chambers (RPC) and Outer Hadron Calorimeter (HO).

Regarding the long term operation of the DT system, in order to cope with up to a factor 2 nominal LHC luminosity, several improvements will be implemented. The in-chamber local electronics will be modified to cope with the new rate and radiation environment.

This paper will present, along with the main system improvements implemented in the system, the first performance results from data collected at 13 TeV center-of-mass energy during 2016, confirming the satisfactory operation of both DT performance and the TwinMux system. A review of the present status and plans for the DT system upgrades will be also described.

KEYWORDS: Large detector systems for particle and astroparticle physics; Muon spectrometers; Performance of High Energy Physics Detectors; Trigger detectors
1 Introduction

The Large Hadron Collider (LHC), the CERN proton-proton collider, operates since 2010 at a centre of mass energy that, starting from 7 TeV, reached 13 TeV in 2015.

The Compact Muon Solenoid (CMS) is a multi-purpose experiment placed in one of the LHC interaction points. A transversal view of CMS experiment, with focus in the Muon System, is shown in figure 1. The Muon System is composed by three different technologies: Drift Tubes (DT) chambers in the barrel, where the magnetic field is uniform and the background rate is relatively low (< 10 Hz/cm²), Cathode Strips Chambers (CSC) in the endcap and, to give strength and redundancy to the muon system, several layers of Resistive Plate Chambers have been installed both in the barrel and in the endcap.

The DT system is composed by 4 concentric stations (figure 2 left), for a total of 250 chambers. The total number of DT elementary channels (figure 2 right) is about 172000. A more detailed description of the CMS detector can be found in [1].

2 DT performance during 2016

The online operation of the DT system within the CMS experiment was excellent since 2010, when the first LHC data were collected. During 2016, despite major upgrades of the L1 Trigger System, only few minutes of collision data taking were lost and only a negligible fraction of the collected data will not be used for analysis due to DT problems.

Starting from 2010, at the beginning of the LHC operations, the fraction of non active channels in the DT system increased of about 1% per year (figure 3): most of these problems are due to hardware failures of the electronic boards placed on the detector, which constitute the first layer of the DT trigger and readout chain. These boards are accessible only during LHC Long Shutdowns
Figure 1. One quadrant of the CMS detector in its Run II configuration (from 2015), with the Muon detectors in colour: DT chambers (MB) in orange, CSC chambers (ME) in green and RPC chambers (RB and RE) in blue.

Figure 2. Transversal view of the CMS barrel (left) and DT elementary cell (right).

(LS): the first one (LS1) took place during 2013 and 2014 and most of the problematic channels were recovered. At the end of proton physics operation of 2016, 98.8% the DT channels were active.

The DT efficiency to detect a single hit (figure 4) was defined and measured as the ratio between the number of detected and expected hits. The position of expected hits was determined using sets of well reconstructed track segments: at least 7 or at least 3 hits were required to be associated to a segment, in the $\phi$ and $\theta$ view respectively (A chamber consists of 8 layers that measure the $r$-$\phi$ coordinates and 4 orthogonal layers that measures the $r$-$z$ coordinate, except for MB4, which has only 8 $r$-$\phi$ layers). Moreover the segment itself was required to cross the chamber with an
Figure 3. Fraction of DT active channels as a function of time, starting from beginning of Run I operation (2010).

inclination lower than 45 degrees. The intersection of such a high quality track segment with a DT layer determined the position of the expected hit. The cell is considered efficient if a hit is found within the tube where it is expected to be.

| Entries | Mean | RMS | Underflow |
|---------|------|-----|-----------|
| 250     | 98.53| 0.3795 | 0         |

Hit Efficiency [%]  
75 80 85 90 95 100

Figure 4. DT single hit efficiency for chambers.

Figure 5 shows the DT single hit resolution. The resolution was computed from the width of the distribution of the observed distance ("residual") between any reconstructed hit and the fitted segment it belongs to. Ideally, any hit for which the residual is being computed should be excluded from the segment fit, but this procedure is extremely demanding in terms of CPU time. For this reason, segments were fitted only once, keeping all compatible hits. Analytically-computed correction factors were then applied to the widths of residual distributions, in order to correct the bias and derive final results for hit resolution. The resolution in the \( \phi \) layers (i.e. in the bending plane) is better than 250 \( \mu m \) in MB1, MB2 and MB3, and better than 300 \( \mu m \) in MB4. In the \( \theta \) layers the resolution is always better than 500 \( \mu m \) except in the external wheels of MB1 (because of the track inclination and the effect of the transverse component of the magnetic field [2]).
2.1 DT Trigger upgrade performance

The DT L1 Trigger electronics in-detector has the goal, for each chamber, to select the trigger candidate segments (trigger primitives), to measure their position and direction and to provide the bunch-crossing identification. The trigger primitives are then sent outside the experimental cavern, in the CMS counting room, where the muon trigger candidates are reconstructed and selected.

During the winter shutdown 2015/2016 a major upgrade of the CMS L1 Muon Trigger system (with the exclusion of the in-detector electronics) took place. The new system, more powerful, is based on $\mu$TCA cards. Moreover, the trigger architecture was redesigned: the old sub-detector centric concept was replaced by a geographical one. Until 2015 the trigger informations of each muon system (DT, RPC and CSC) were collected only at the end of the trigger chain. With the new design an early combination of information is possible at the trigger primitive level, before the muon tracks are fully reconstructed. In 2016 the full potentiality of this new architecture was not completely exploited.

The performance of the DT Local Trigger (DTLT) was checked using 2016 data and compared with 2015 data. The DTLT efficiency was defined and measured as the ratio between the number of observed and expected triggers. The expected triggers were defined requiring the presence in a chamber of a track segment, reconstructed in both $\theta$ and $\phi$ views, belonging to a “Global Muon” matched with the inner tracker, and having at least 4 associated hits in the $\phi$ layers (minimum number of hits required to build a trigger primitive). At least two other stations were required to deliver trigger primitives in the event, in order to avoid the bias of self-triggering stations. The DTLT was then considered efficient if a trigger primitive was delivered at the correct bunch crossing in the same chamber. Figure 6 shows the DTLT efficiency versus the global muon transverse momentum, comparing 2015 and 2016 results: the first goal of the trigger upgrade was to reproduce the 2015 performance. The full potentiality of the new L1 Trigger architecture (see section 3.1) will be exploited starting from 2017.

Figure 5. DT single hit resolution as a function of station MB1 (closest to IP), MB2, MB3, MB4 (outermost station) and wheels (W-2, W-1, W0, W1, W2). Different wheels correspond to the z segmentation as shown in figure 1.
Figure 6. DT local trigger efficiency, station by station, versus the global muon transverse momentum, pT, compared to the measurement from 2015 data.

3 DT future improvements during 2017

3.1 L1 Trigger upgrade

The upgrade of the muon trigger aimed at exploiting the redundancy of the three muon detection systems earlier in the trigger processing chain in order to obtain a high-performance trigger with higher efficiency and better rate reduction.

The good performance of the L1 muon trigger system can be seen in figure 7, were the single muon trigger efficiency is plotted as a function of the offline reconstructed muon pseudo-rapidity: in the barrel region (|\eta(Reco \mu)| < 0.8) the efficiency in generally larger the 95%. However, in the same plot, the drop of efficiency around |\eta| = 0.2 is clearly visible, generated by the geometrical gap between the wheels that constitute the muon barrel system.

The L1 upgraded system can help to mitigate this inefficiency: the information of different sub-detector (mainly DT and RPC, but also HO, the external layer of the Hadronic Calorimeter placed outside the magnet solenoid) can be combined earlier, exploiting the good DT spatial resolution with the excellent RPC timing resolution (figure 8). This new configuration of the system was already partially tested during 2016 data taking.
Figure 7. Single muon trigger efficiency (18 GeV $p_T$ threshold) as a function of the offline reconstructed muon pseudo-rapidity.

Figure 8. Distribution of the bunch crossing (BX) of RPC reconstructed hits associated with global muons in the barrel (2011 data) with respect to Level 1 Accept trigger (L1A).

3.2 Readout upgrade

In order to cope with luminosity up to a factor two larger than nominal LHC, the second level of the readout system of the CMS DT electronics needs to be redesigned to minimize event processing time and remove present bottlenecks: these new boards ($\mu$ROS) are $\mu$TCA modules (TM7). Each board collects the information from up to 72 input links (3 DT sectors), requiring a total of 23 boards. The installation of the upgraded readout system is foreseen for the end of 2017: the production of $\mu$ROS boards and procurement of the different system components is ongoing. A development
μTCA crate has been installed in the CMS service cavern, equipped with one TM7 spare board. An optical fibre splitter has been installed to feed live collision data from the chambers and allow development and validation of FW and SW before the 2016 year end technical stop.

4 DT longevity studies for High Luminosity LHC

After the end of LHC operations in 2023, the plans for the accelerator are to start the program of the High Luminosity LHC (HL-LHC) in 2026. The goal of the LHC upgrade is to increase the instantaneous luminosity up to $5 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$ (eventually up to $7.5 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$) and to reach an integrated luminosity of 4000 fb$^{-1}$ over 10 years of operation (figure 9). This will substantially enlarge the mass reach in the search for new particles and will also greatly extend the potential to study the properties of the Higgs boson discovered at the LHC in 2012.

![Figure 9](image)

**Figure 9.** Plans for HL-LHC instantaneous and integrated luminosity [5].

In order to achieve these goals, that include an important program of analysis with muonic final states, the performance of the Muon system must be stable over the years of operation in this challenging experimental environment. Therefore, it is vital to evaluate the longevity of the DT chambers and electronics, as well as the performance of the system in the HL-LHC environment: the expected dose accumulated in the DT chambers at the end of the HL-LHC program is about 0.5 Gy (figure 10) in the most problematic regions, where the hit rate due to the background could reach 25 Hz/cm$^2$.

A new Gamma Irradiation Facility (GIF++) [3] has been built by the CERN Engineering- (EN) and Physics- Department (PH) to meet these challenges. GIF++ is located in the North Area of the CERN Super Proton Synchrotron (SPS) where a high flux of gamma radiation (662 keV) produced by 13.9 TBq $^{137}$Cs source is combined with a 100 GeV muon beam. An attenuator system is installed to vary the gamma flux on both sides of the source independently. A schematic overview of the GIF++ is shown in figure 11. The higher source activity will produce a background gamma field which is a factor 30 more intense than that at original GIF, allowing to accumulate doses equivalent to HL-LHC experimental conditions in a reasonable time.
**Figure 10.** Transversal view of the simulated dose accumulated in the CMS detector after 3000 $fb^{-1}$ delivered by LHC.

**Figure 11.** An overview of the GIF++.

A DT spare chamber is installed in the down-stream region of the GIF++ irradiator ($\gamma$-field 1 in figure 11). Goals of DT studies at the GIF++ are:

1. Test the standard operation under HL-LHC background levels.

2. Study the performance for different High Voltage values in order to identify more conservative settings to maximize chamber lifespan.

3. Irradiate the DT chamber to accumulate the integrated charge per wire expected in the HL-LHC environment.
Moreover, it’s already known [4] that the in-detector electronics is expected to heavily deteriorate after the Long Shutdown 3 (2025). This electronics, that constitute the first layer of the DT trigger and readout chain, will be replaced before the beginning of HL-LHC operations.

The background rate is constantly monitored during normal LHC operation and a linear dependence from instantaneous luminosity is confirmed up to $1.2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$. In order to mitigate the effect of the neutron-induced background in the ageing of the DT chambers, different shields are under test in the external stations of the muon barrel system. The most promising shielding, that will be installed during the Long Shutdown 2 (2019–2020) in all the external DT stations of the top sectors, is composed with 3 cm of borated-polyethylene plus 7 mm of lead: with this configuration, a rate reduction of 50% is achieved.

5 Conclusion

In this paper, the performance of the Drift Tubes system during LHC operation has been presented: the detector, as well as the full CMS Muon System, is operating efficiently since the beginning of LHC operation in 2010. In order to cope with the increased LHC luminosity, several upgrades have been done. In particular, a new trigger system has been designed, to combine the trigger information from DT and RPC before of the reconstruction of muon tracks. More efficient trigger algorithms, with a better $p_T$ resolution, can be used in the L1 trigger chain: the full potentiality of this new architecture will be achieved during 2017 data taking.

HL-LHC will be a challenging environment for the DT system: several tests are ongoing to ensure the same performance of the muon system for the full lifetime of CMS.

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