The Compact Muon Solenoid Experiment

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Performance and Future Upgrades of the CMS Drift Tube Muon Detector

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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. The DT system keeps evolving in order to cope with long term operational challenges, as well as future constraints for rate reduction imposed by future increases of LHC luminosity, maintaining the highest possible efficiency. During the first long LHC shutdown (LS1) a significant number of improvements and upgrades started being implemented, in particular concerning the readout and trigger electronics. Ever since LS1, each LHC winter shutdown is used to install and test these new developments towards HL-LHC. Regarding the long term operation of the DT system, in order to cope with up to a factor 2 nominal LHC luminosity, several modifications will be required. The in-chamber local electronics will be modified to cope with the new environment. Also the second level of the readout system needs to be redesigned to minimize event processing time and remove present bottlenecks. This talk will present, along with the main system improvements implemented in the system, the current performance results from our detector, using data collected at 13 TeV center-of-mass energy, confirming the satisfactory operation of both DT. Also the talk will review the present design, status and plans for the future DT system upgrades towards HL-LHC.

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Performance and Future Upgrades of the CMS Drift Tube Muon Detector

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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 region relies on Drift Tube (DT) chambers. The DT system keeps evolving in order to cope with long term operational challenges, as well as future constraints for rate reduction imposed by expected increases of LHC luminosity, while maintaining the highest possible efficiency.

The main system improvements implemented, as well as the current performance results from the detector are described here, confirming the satisfactory operation of DT. Also, the present design, status and plans for future DT upgrades are reviewed in this document.

Keywords: LHC, CMS, gaseous detectors, drift chambers, muon

I. INTRODUCTION

THE CMS Muon Detector is an efficient tracking system composed of several detector technologies that provide a robust trigger, redundant against background. The central region of CMS is equipped with Drift Tube Chambers used as tracking and triggering devices. A total of 250 chambers are uniformly distributed among 5 barrel wheels, filling the gaps of the return yoke. Each wheel hosts four concentric rings of stations segmented in 12 contiguous sectors. The position of the chambers can be seen on figure 1.

Fig. 1. Detail of the 4 Drift Tube stations present in each wheel sector

The basic DT detector element is a rectangular drift cell with a transversal size of 4.2 cm x 1.3 cm, as shown in figure 2, filled with an 85/15% Ar/CO₂ gas mixture.

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Fig. 2. Lateral cut of a DT layer.

Cells are arranged in parallel to form detection layers, stacked half-staggered in groups of four to form super-layers (SL). Each DT chamber is equipped with two SLs measuring the coordinate in the CMS bending plane ($r - \phi$), whereas a single SL measures the coordinate along the beam line (z) in the 3 innermost station rings.

The CMS DTs measure resolution, for single reconstructed hits, is around $\sim 250 \mu\text{m}$, for a final resolution of $\sim 100 \mu\text{m}$ for offline segments reconstructed in the $r - \phi$ view.

II. RECENT DT SYSTEM IMPROVEMENTS

In 2013-2014 the Large Hadron Collider (LHC) was stopped for a shutdown period, called Long Shutdown 1 (LS1), during which it was upgraded. A second period (Run-II) of data taking started at the beginning of 2015. The center of mass energy was increased from 8 to 13 TeV, and the number of interactions per collision and the instantaneous luminosity have reached the values of 50 and $1.5 \cdot 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ respectively.

Due to this upgrade the first trigger level (L1) of CMS had to cope with an increase in the total event rate of roughly a factor 6.

LS1 allowed to implement a significant number of improvements and upgrades, in particular, inside DT, concerning the readout and trigger electronics. The most significant change was the relocation of the second level of readout and trigger electronics from the experimental cavern to the contiguous service cavern (USC) [1], which is accessible even during LHC runs. This operation allows to replace and update this part of the readout and trigger chain independently from LHC stops.

A. Trigger

Before the installation of the trigger upgrade, the trigger signals from different muon subdetectors were only combined at the last stage in the Global Muon Trigger (GMT).

During the 2015 year-end run break, new trigger electronics, able to combine information of DT trigger segments with the one of the nearby Resistive Plate Chamber (RPC) layers was deployed, as part of a major upgrade of the CMS muon trigger.

The new trigger approach takes advantage of the different characteristics of the muon detectors (excellent position resolution from DT and excellent timing from RPC) earlier in the trigger primitive generation chain in order to obtain a high-performance trigger with higher efficiency and better rate reduction. Since every additional hit along a muon trajectory further improves the fake rejection and muon momentum measurement, the upgrade seeks to combine muon hits at the input stage of the Muon Track-Finders layers rather than at its output. All the hits should then contribute to the track irrespectively of the sub-system that detects them.

The solution installed to fulfil the new requirements was the TwinMux [2], a μ TCA board based around a Virtex-7 FPGA with embedded optics for high speed data transmission.

Fig. 3. TwinMux board with highlights on the different components

The TwinMux system replaced the old TSC electronics with a much more powerful system that also combined the output of several detectors (DT, RPC and HO).

Together with a hardware upgrade a new control software was implemented. The SoftWare for Automating conTrol Common Hardware (SWATCH) acts as a common interface for all the trigger subsystems, providing monitoring and minimizing the manpower needed for operating the system.

B. Readout

The first stage (on-chamber) of the DT RO system are the Read-Out Boards (ROB), that digitise with 0.71 ns time bin 128 DT chamber wire signals. ROB send their data to the Read-Out Server (ROS) and Device Dependent Unit (DDU) boards that will be replaced with the Micro Read-Out Server (μ ROS) [3] system in order to cope with the increased luminosity.

Fig. 4. Diagram of the DT Readout electronic chain

Simulations show that the ROS processing time is the current most severe bottleneck in the readout chain. Their performance in the presence of evenly-distributed background noise that will be present with increased luminosity will be affected.

The new μ ROS boards share the TwinMux hardware platform with different firmware. Each μ ROS can receive up to 72 input links at the low rate of 240 Mbps. The input information is merged into a single event block with proper data quality monitoring and synchronization features. The output information is sent by a high speed (10 Gbps) link through the backplane to an AMC13 board that collects the links from each crate and forwards it to the CMS Data Acquisition System (DAQ).

There will be 23 μ ROS boards in the final system, distributed in 3 crates (negative, central and positive CMS barrel wheels).

Currently all the boards have been assembled and have been test. A crate containing 10 boards has been installed in USC with input links shared with the ROS through an optical splitter. The μ ROS test crate has been successfully integrated with the central DAQ system and is currently taking collision data together with the production system.

The performance of these new boards has been tested during 2017 with the idea to finalize their installation for the 2018 data taking period.

III. DT PERFORMANCE

The TwinMux upgrade has allowed the possibility to merge output of both DT and RPC chambers to create a “Trigger SuperPrimitive”.

Fig. 5. Diagram of the RPC + DT trigger generation.

An RPC cluster closest to a DT trigger segment ($\Delta\phi < 15$ mrad) in a time window 3 BX wide is considered matched. In this case, the output trigger primitive is composed by the spatial measurements (position, angle) provided by DT, while the time measurement (the BX) is taken from RPC. Using RPC hits in trigger primitive building results in a trigger-primitive-finding efficiency improvement of 1.4% on average, as shown in figure 6.

Fig. 6. Trigger primitive efficiency as a function of the pseudorapidity with DT trigger segments and DT+RPC SuperPrimitives.

IV. UPGRADE PLANS

Future upgrades of the LHC accelerator will increase its integrated luminosity by a factor 10 with respect to the original design. In order to cope with this increase, both from the point of view of the augmented multiplicity and the ageing caused by longer operational life, the DT detector will undergo a major refurbishment. The on-chamber local electronics will be modified to cope with the new environment.

Fig. 7. Diagram of the trigger and readout during Phase I and Phase II.

In the present design, the first level of trigger and readout electronics are placed on the detector, in embedded structures called “minicrates” (MCs). Several components within the MCs are not qualified for operation during HL-LHC. The readout is limited to less than 300 kHz trigger rate, they are complex to maintain and present a high power consumption. This problem will be solved by replacing the MCs with a much simpler on-detector system. New electronics based on Flash-FPGA, implementing TDCs with time resolutions of 1 ns, and a chipset for optical data transmission will replace the current design and move the trigger and readout logic outside

the detector. The new TDCs will operate in trigger-less mode, and a continuous optical stream of digitized hits will be sent to USC. The L1 trigger functionalities will also be moved to USC together with the DAQ.

The new architecture will represent a significant improvement of the trigger performance, since full time resolution of the hits will be available (1 ns vs 12 ns), and the dead time will be reduced from 400 to 100 ns. Locating the trigger logic off-detector allows to compute multiple chambers in the same processor, and combine the DT/RPC/HO information. Currently several R&D efforts are ongoing for the development of new tracking algorithms, both for chamber segment building and for full standalone muon tracking.

Fig. 8. Picture of the Phase II demonstrator.

A demonstrator is being developed, as shown in figure 8. A fully functional DT chamber was provided with all the services needed for operation: high voltage, gas flow, cooling and a complete chain of electronics for trigger and readout.

The electronic setup contains two branches:

- The legacy part uses the electronics currently under operation in the main experiment: Minicrate for on-detector electronics together with TSC and ROS for trigger and readout backend, respectively.
- The upgrade part is composed by the new design based on Virtex 7 FPGAs and a full μ TCA design in the form of a special μ ROS for trigger and readout.

V. LONGEVITY AND AGING MITIGATION

The increase in luminosity will also entail a higher dose rate. The effects of radiation on electronics are well known and were taken into consideration when designing the system and choosing components.

Additionally, it will require the non-upgraded part of the system, in particular the chambers, to withstand an integrated dose one order of magnitude larger than initially designed for. The effects on the detector itself, validated for LHC during CMS construction, need further testing to reach the required irradiation for HL-LHC. Although the gas mixture, Ar/CO₂, is safe from the radiation point of view, outgassing from the chamber materials could generate deposits on the wire.

In order to characterize the effects of radiation on the detector, a spare chamber was installed in the Gamma Irradiation Facility (GIF++) [4] at CERN. It provides a high energy particle beam coming from the Super Proton Synchrotron (SPS) and a high activity $^{137}\text{Cesium}$ source that can be used to integrate the total dose that will be deposited in the detector during the whole operation of HL-LHC in a reasonable amount of time.

The DT chamber was placed under a controlled irradiation field while monitoring the dose rate and current on the wires. The measurement of the received dose is critical to extrapolate the results to the CMS experiment. Dose has been characterized using different methods to improve the precision of the total integrated dose accumulated. A radiation sensitive transistor as well as a proportional chamber and a portable Geiger-Müller tube for localized measurements have been used. The total integrated charge has been calculated from these dose measurements and it is represented versus time in figure 9.

Fig. 9. Integrated charge per centimeter as a function of the days of irradiation at GIF++. Around 15% percent of the expected total luminosity provided by 10 years of operation of HL-LHC has been accumulated during 15 days of irradiation of a DT chamber at GIF++.

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