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Upgrade of the Drift Tube (DT) Muon System for the CMS Detector at the HL-LHC

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The High-Luminosity Large Hadron Collider (HL-LHC) project aims to boost the performance of the LHC, augmenting the potential for discoveries and the accuracy of SM measurements. From the LHC Run-4 onwards, the upgrade aims at increasing the instantaneous luminosity of the machine, to target an overall ten-fold increase of the collected dataset compared to the LHC initial design. In order to withstand the expected increase of both integrated doses and event rates, the on-board electronics hosting the first level of readout and trigger of the CMS Drift Tube (DT) chambers will be replaced with the new On-Board electronics for DT (OBDT). Time digitization (TDC) data from the OBDTs will be streamed directly to an upgraded back-end system that, relying on the latest commercial FPGAs, will perform event building and generate trigger primitives (TP) exploiting the ultimate DT cell resolution. Additionally, the Detector Safety System (DSS) will also undergo a redesign, which entails the development of a new hardware, called MONitor for SAfety (MONSA) system. To demonstrate the Phase-2 architecture, a readout based on early OBDT prototypes was deployed in parallel to the legacy electronics through front-end splitting on a full DT sector. Data from the OBDTs is streamed into proxy back-end boards, where the trigger primitive generation algorithm designed for the upgrade is run. In parallel, close-to final prototypes of the OBDTs were assembled and test under radiation. In this report, the motivation for such an upgrade will be highlighted and the status of the development and testing of the DT Phase-2 electronics at large will be discussed. Moreover, the most up to date performance results from the DT slice-test operation will be presented, as well as the plans to augment the demonstrator using final OBDT prototypes.

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1. The CMS drift tubes

The Compact Muon Solenoid (CMS) muon system effectively identifies muons, triggers them, and precisely reconstructs their kinematics for a variety of physics analyses. The energy of muons originating from proton-proton collisions provided by the CERN Large Hadron Collider (LHC) spans from a few GeV to one (or few) TeV. CMS can produce a phenomenal muon performance by integrating data from a silicon-based inner tracker with a muon system made up of several types of gaseous detectors. The CMS muon-system barrel is equipped with chambers built of rectangular drift tubes (DTs), which are filled with an 85/15% Ar/CO_2 gas mixture and are designed to ensure an almost uniform drift velocity of around 55μm/ns. The CMS DT precise position measurement enhances the accuracy of offline high-energy muon tracking in addition to being used for muon identification. The Level-1 Trigger receives online track segments from the DTs (L1T).

A total of 250 DT chambers cover the full CMS muon-system barrel. They are arranged into 4 concentric station rings (MB1 to MB4) grouped in structures named wheels, that are replicated five times parallel to the beam line (W-2 to W+2). Each wheel is further subdivided into 12 sectors slices (S1 to S12). Chambers consist of multiple layers of parallel DT cells. Every chamber is equipped with 8 layers measuring the trajectory of incoming particles along the transversal (r - ϕ) plane. Furthermore, chambers installed in MB1, MB2 and MB3, also host groups of 4 layers measuring the trajectory along the longitudinal plane. Within a chamber, straight line segments reconstructed in r - ϕ feature an efficiency above 99%, and a position (time) resolution around 100 μm (2-3 ns). Similarly, dedicated on-board electronics, sampling the cells responses every 12.5 ns, builds L1T segments (or trigger-primitives — TPs) that can identify the parent bunch-crossing from which a muon originated with 98% efficiency, and have a position resolution of 1 mm.[1]

Accelerated ageing study shows that, the performance degradation of the DT chambers expected during operation at the High-Luminosity LHC (HL-LHC) is acceptable [2]. The DT readout and trigger electronics, on the other hand, must be replaced because the on-board components will not withstand the radiation conditions of the HL-LHC. In addition, an upgrade of the L1T and readout is necessary to withstand the increase in instantaneous luminosity anticipated at the HL-LHC [3]. As a result, the Phase-2 DT upgrade (also known as the HL-LHC DT upgrade) includes replacing the current electronics. New On-Board DT electronics (OBDTs) will continuously stream high resolution time-to-digital converter (TDC) counts to a new back-end hosted in the CMS service cavern by means of optical fibers. The upgraded back-end will perform slow-control and event-matching and reconstruct online TPs using the ultimate DT cell resolution, significantly improving the trigger segment precision.

2. DT slice-test for Phase-2

During the LHC long shutdown 2, four chambers of W+2 S12 were equipped with the prototype version 1.0 of the OBDT known as the DT slice-test (Fig 1). The signals from the front-end electronics of all slice-test chambers are split and sent in parallel to the OBDTs and further to the prototype back-end electronics. A total of 13 OBDTs are installed to cover all 4 DT chambers of the slice-test, whereas, for the back-end, a total of 5 boards (called AB7) perform event-matching and Trigger Primitive (TP) reconstruction. The slice-test is integrated within the CMS central

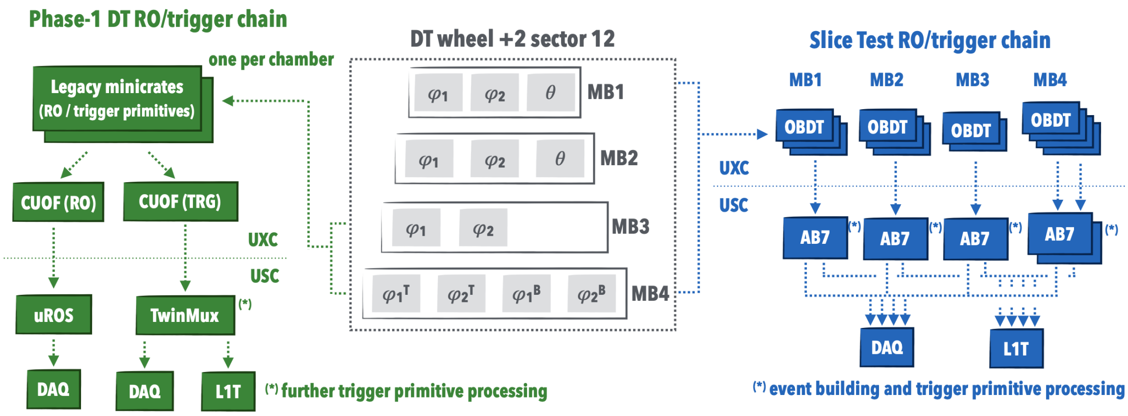

Figure 1: Diagram comparing the DT readout (RO) and trigger chains as they are in the Phase-1 system and in the DT slice-test. The central part of the fig highlights how many Phase-2 on-board DT electronics (OBDT) boards are installed in each DT chamber. The left part of the diagram describes the Phase-1 system: readout and trigger primitive generation are performed by the legacy on-board DT electronics (Minicrates). The right part of the diagram describes the slice-test: TDC data is streamed by each OBDT to AB7 boards, which are in charge both of event building and trigger primitive generation.

data acquisition (DAQ), the detector control system and the offline software. It has been regularly operated since summer 2019, and was included in central CMS data-taking campaigns.

The slice-test (Phase-2) readout efficiency is measured, channel-by-channel, by looking for the presence of a slice-test hit when a corresponding hit is recorded by the present (Phase-1) readout. Results are reported in Fig 2 (left). Apart from few masked cells, efficiency is compatible with 100%. Afterwards, the consistency of the TDC time information between Phase-1 and Phase-2 is validated, and a calibration routine (which includes channel-by-channel equalization) is run on data from both readouts, to correct and align the raw TDC time measurements with a precision within 1 ns. Offline segments are then built in parallel using Phase-1 and -2 data, and are compared. Figure 2 (center) shows the crossing time of cosmic muons measured by Phase-1 and Phase-2 segments. Finally, calibrations (including channel-by-channel equalization) are deployed in the AB7 firmware to maximize the performance of the TP generation. Figure 2 (right) shows the difference between the muon crossing time measured with TPs and offline segments. Phase-2 TPs (blue) show a much better time resolution (few ns), when compared with the Phase-1 TPs (red), which can only perform bunch-crossing identification [4].

3. Summary and planing

The Phase-2 DT electronics prototypes were installed and tested as part of the CMS Drift Tubes (DT) Slice-Test. The new system is successfully incorporated into CMS and is currently operating pretty well. The trigger performance improvement anticipated by the Phase-2 DT upgrade is already largely evident, despite the fact that algorithms are still developing. A big achievement in the DT upgrade program is the operation of the slice-test over LHC Run-3. In addition, a pre-production batch of the OBDT nearly finished version was just made available and will be used in the upcoming slice-test which is proposed for the W+2 S1 in the Year End Technical Stop (YETS) 2022.

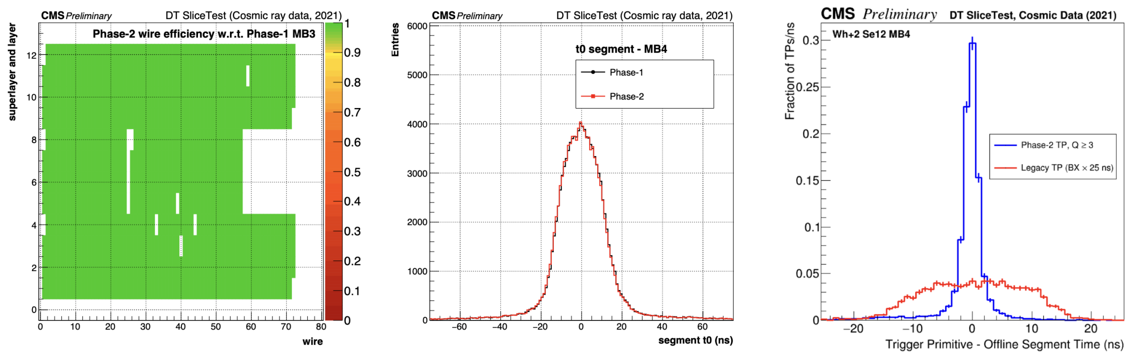

Figure 2: Left: slice-test hit detection efficiency measured, channel by channel, relative to the Phase-1 one. Centre: crossing time of cosmic muons, as measured by segments reconstructed out of slice-test and present readout data. Right: trigger primitive time resolution measured with respect to the offline segments for slice-test (blue) and present trigger (red) TPs.

Moreover, there have been developments on several fronts in terms of DT upgrades. The new Minicrate mechanical design is finalized and production has already started. Additionally, the integration of the Muon Barrel Trigger back-end is ongoing with the prototype cards based on the ATCA system. The prototype of the DSS MONSA (Monitoring and Safety) board is produced and its integration with the OBDTs has already been achieved.

References

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[4] CMS Drift Tubes public results: https://twiki.cern.ch/twiki/bin/view/CMSPublic/DtPublicResults.