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CMS DRIFT TUBES AT HIGH-LUMINOSITY LHC: CHAMBER LONGEVITY AND UPGRADE OF THE DETECTOR ELECTRONICS

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Drift Tubes (DT) equip the barrel region of the CMS muon spectrometer serving both as a tracking and a triggering detector. At the High-Luminosity LHC (HL-LHC), they will be challenged to operate at background rates and withstand integrated doses well beyond the specifications for which they were initially designed. Longevity studies show that, though a certain degree of ageing is expected, a replacement of the DT chambers is not needed for CMS to operate successfully at the HL-LHC. On the other hand, the onboard readout and trigger electronics which presently equip the chambers are not expected to cope with the harsh HL-LHC conditions. For this reason, they will be replaced with time-to-digital converters (TDCs) streaming hits to a backend electronics system where trigger segments reconstruction and readout event matching will be performed. This new architecture will allow to operate local reconstruction on the trigger electronics exploiting the full detector granularity and the ultimate DT cell resolution. Already over the second LHC long shutdown, a slice-test system consisting of four DT chambers will operate using the upgraded electronics, as an early test of the HL-LHC DT setup. In this document we outline the present knowledge about the DT detector longevity. Furthermore, we describe the prototype electronics and backend demonstrators, as well as the state-of-the-art of the local trigger algorithms that are being designed to run in the upgraded DT system. Performance measurements of the upgraded DT trigger, based on simulations, will be presented. The status of the operation of the DT slice-test will be also covered, with emphasis on the status of the implementation of the trigger algorithms in hardware.

Keywords: HL-LHC, CMS, Muon System, Drift Tubes

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1. The CMS Drift Tubes and the High-Luminosity LHC

The Compact Muon Solenoid (CMS) is a general-purpose experiment operating at the CERN Large Hadron Collider (LHC). The signatures of many of the analyses performed as part of the CMS physics programme involve muons with a transverse momentum (p_T) that spans a range from a few GeV to approximately 1 TeV. For this reason, CMS is equipped with a muon system which: *(i)* allows for an efficient offline identification of muons, *(ii)* provides standalone triggering capabilities, and *(iii)* improves the measurement of the p_T of muons with energies greater than a few hundreds of GeV. The muon system is hosted in the return yoke surrounding the CMS superconducting magnet, and consists of different types of gaseous detectors. In the barrel region, where particle fluxes are low and the magnetic field is uniform, CMS is equipped with Drift Tubes (DT) detectors, covering a pseudorapidity range ($|\eta|$) up to 1.2, and serving both as tracking and triggering devices. CMS hosts 250 DT chambers, arranged parallelly into 5 *wheels* of identical layout, called YB-2 to YB+2. Each wheel consists of four concentric rings of *stations*, called MB1 to MB4, and each station ring is built of 12 *sectors*. Within a DT chamber, single cells are arranged parallelly to form *layers* and groups of four layers are arranged half staggered to form *superlayers* (SL). Chambers in DT stations from MB1 to MB3 are equipped with three SLs, two of them measuring the muon trajectory in the bending (R-ϕ) plane and one of them measuring the coordinate along the longitudinal (R-z) plane. Chambers from the MB4 station are, instead, equipped only with two SLs measuring the position in R-ϕ. Within each chamber, muons crossing the DT system are reconstructed as straight-line track segments both offline and in the trigger. In the offline reconstruction, segments are built with an efficiency close to 100% and a spatial resolution of around 100 μm, whereas trigger segments (or *trigger primitives*) are built with an efficiency of about 95% and are characterized by a position (direction) resolution of 1 mm (up to 5 mrad).

An upgrade of the LHC, called High-Luminosity LHC (HL-LHC) [1] will start its operations in 2026. In its design (ultimate) upgrade scenario, HL-LHC is expected to provide 14 TeV proton-proton collisions at instantaneous luminosities up to ~ 5 (7.5) $\cdot 10^{34}$ cm^{-2}s^{-1}, and collect a total integrated luminosity around 3000 (4000) fb^{-1}. These numbers have to be compared with a maximum instantaneous luminosity up to $2.2 \cdot 10^{34}$ cm^{-2}s^{-1} and ~ 150 fb^{-1} of 13 TeV proton-proton collision data collected by CMS over the LHC Run 2. At the HL-LHC, the CMS DT will be challenged to withstand particle fluxes and integrated doses that exceed the original system specifications. Therefore, the longevity of the detectors themselves, as well as the one of their onboard electronics, must be re-assessed under these new assumptions. In addition, to preserve acceptance for physics signatures at the electroweak scale, the CMS trigger will need to be redesigned to operate at much higher rates. This will also impact the DT readout and trigger electronics. In the following sections, the studies to assess the longevity of the DT in conditions as the ones foreseen for the HL-LHC are presented, together with the strategy for the Phase 2 upgrade of the DT electronics and the current status of the testing of Phase 2 component prototypes.

2. CMS Drift Tubes longevity studies

The integrated charge per wire and the total ionization dose expected for the most irradiated DT chambers at the HL-LHC (assuming instantaneous and integrated luminosities according to its design scenario), are respectively of 20 mC/cm and 1.2 Gy [2]. Using these numbers as reference, the DT chamber longevity is assessed exploiting the Gamma Ray Irradiation Facility at CERN (GIF++). The GIF++ provides a 14 TBq ^{137}Cs source emitting 662 keV photons, which is used to irradiate detectors, and to generate background for studies with muon beams, which are also provided by the facility. The results reported in this document refer to two irradiation campaigns, performed on a spare DT MB2, that allowed to integrate a total ionization dose approximately as large as twice the maximum one expected for DT at the HL-LHC. Only two layers from a DT R-ϕ SL were kept on during the irradiation campaign, whereas ageing was prevented in the rest of the chamber by keeping it in standby. Efficiency of the aged layers was measured in dedicated runs with muon beams or cosmic rays, where the full chamber was turned on. The SLs that were kept in standby during the irradiation campaign were used to reconstruct segments, that were then extrapolated to the aged layers, in order to identify the DT cells where to compute efficiency. Measurements were performed at different points along the irradiation campaigns and, for a given irradiation point, they were repeated modulating the background generated by the GIF++ source with absorbers. Values of dose rates (total integrated doses) were scaled to expected instantaneous (integrated) luminosities, by comparing the DT wire currents (integrated charges) measured at GIF++ with the ones measured in the chambers installed in CMS. Out of all the above, the expected performance of DT chambers at different values of HL-LHC integrated and instantaneous luminosities was parametrized with analytical functions, as reported for example in Fig. 1 (left). Depending on their position in CMS, different DT chambers are exposed to different background rates, hence a given value of dose at GIF++ may correspond to different luminosity values, depending on the chamber that is considered for the scaling. Knowing, for each chamber, parametrizations as the one from Fig 1. (left), and assuming as target an instantaneous (integrated) luminosity value corresponding to twice $5 \cdot 10^{34}$ $cm^{-2}s^{-1}$ (3000 fb^{-1}), the expected impact of ageing on the DT hit efficiency was evaluated for all CMS DT chambers to define a, so called, ageing scenario. Within this scenario, inefficiencies due to ageing, are found to be rather large only in the MB1s of YB+/−2, where the efficiency goes down to ~ 61%, whereas, in the rest of the detector, efficiency values range from 80% to 97% (nominal DT cell efficiency). Given the redundancy of the muon system, such values of single hit efficiency are not expected to affect significantly the overall offline muon reconstruction, as shown in Fig. 1 (right).

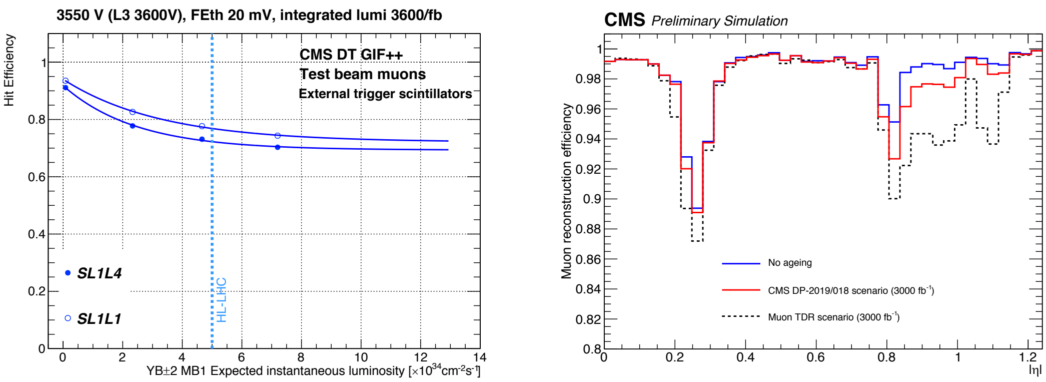

Figure 1. Parametrization of the DT hit efficiency as function of the expected HL-LHC instantaneous luminosity, for an integrated luminosity of 3600 fb^{-1}, based on GIF++ results (left) [3]. Offline muon reconstruction efficiency with and without accounting for inefficiencies due to ageing (right) [3]

3. Algorithms for the upgrade of the Drift Tubes local trigger

Whereas the DT chambers are expected to operate throughout HL-LHC with an acceptable loss of performance, DT onboard electronic components are predicted to fail, if exposed at the level of background rates and integrated doses described in the previous section [2]. Moreover, the present readout and trigger electronics are not designed to cope with a factor 5-7 increase of trigger rate foreseen at the HL-LHC. Therefore, the Phase 2 upgrade of the DT system consists in a replacement of the detector electronics [2]. In the upgraded DT architecture, time digitization (TDC) data will be streamed directly to the new backend electronics hosted in the service cavern, where event building and trigger primitive (TP) generation will be performed using the latest commercial FPGAs. This will allow to build DT TPs which exploit the ultimate detector resolution (few ns), as opposite to the present trigger electronics that processes signals from the DT wires in steps of 12.5 ns.

Two algorithms performing DT TP generation are presently under evaluation. They both process information from contiguous groups of DT cells, and assume that muons follow a straight path inside a chamber. As an initial step, both algorithms exploit the mean-timer property [2], holding for triplets of half staggered drift cells characterised by constant drift velocity, to compute the crossing time of an incoming muon within single SLs. After the crossing time is defined, the *Histogram Based* (HB) algorithm, computes TP slope hypothesis using all permutations of pairs of TDC counts from the cells that satisfy the mean-timer equations. The slope hypotheses are then binned and put into histograms. The coordinate of the bin of the histograms with the highest population is selected as TP slope. A similar logic is run to compute the TP intercept. The HB method processes information from both DT R-ϕ SLs in a single step. The second algorithm, called *Analytical Method* (AM), runs exact formulas from χ^2 minimizations to compute the TP parameters within single SLs, out of DT hits identified with the mean-timer equations. In a second step, the AM method attempt a combination of the TP candidates fitted independently in the two R-ϕ SLs of a DT chamber. If successful, a single TP is built, and its parameters are re-computed to improve their accuracy.

Examples for the performance of these algorithms, computed using simulated samples, are presented in Fig. 2. The left plot shows the efficiency to reconstruct TPs using the HB algorithm in the four DT stations. The right plot shows the position resolution of TPs generated with the AM method computed with respect to offline reconstructed segments. In general, both algorithms are able to build TPs with an efficiency similar to the one of the present trigger, whereas the spatial and time resolution of the new TPs improve significantly with respect to the one of the legacy system, in agreement with the fact that the new trigger algorithms can exploit the ultimate DT hit resolution.

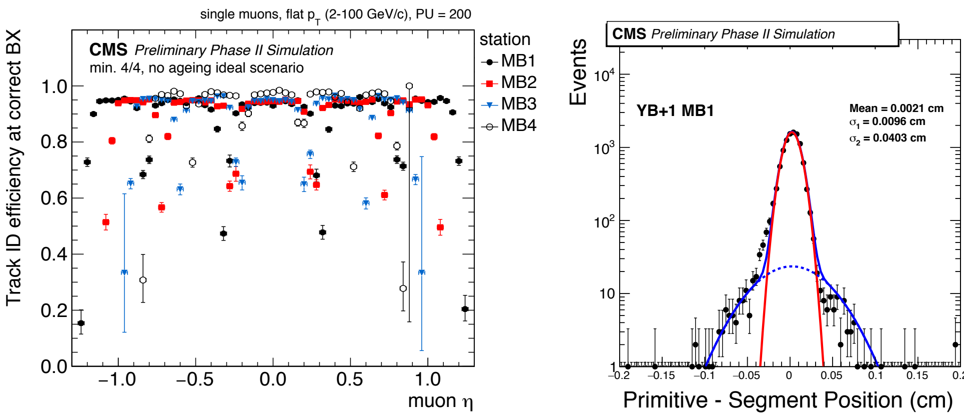

Figure 2. Efficiency of DT TPs generated with the Histogram Based method (left) [3] and position resolution of DT TPs generated with the Analytical Method (right) [3]

4. The Drift Tubes Slice Test exercise

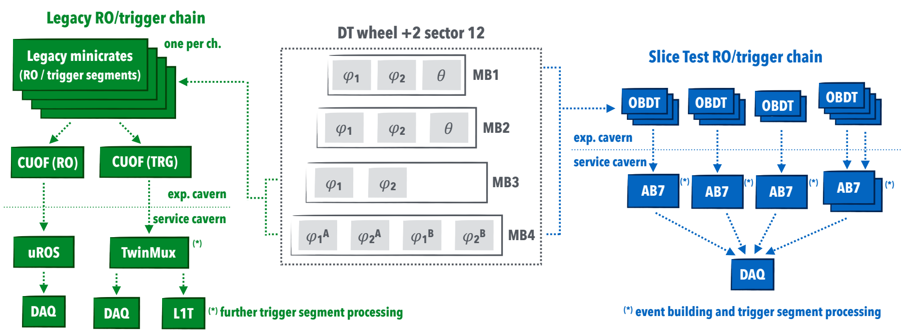

Figure 3. Schema showing the legacy and the upgraded DT readout and TP generation chains as implemented in the DT slice test.

During the second LHC long shutdown, the four DT chambers of a single DT sector (YB+2 sector 12) were instrumented with Phase 2 onboard electronics (OBDT) to setup a demonstrator of the Phase 2 system (DT slice test). In the MB1 and MB2 chambers of the DT slice test, the legacy onboard electronic components have been fully replaced by Phase 2 prototypes, installed with a setup as close as possible to the final one. This is done with the aim of maximising the expertise toward the integration of the new components in view of the full Phase 2 upgrade. On the contrary, in MB3 and MB4, the signals coming from a fraction of the chamber front-ends were instead split and sent to both Phase 2 and legacy electronics. Such setup is aimed to allow for an event-by-event comparison of the response of the Phase 2 and legacy readout and trigger. The OBDT streams TDC hits from the detector directly to the backend electronics, hosted in the service cavern, by means of optical link connections. At present, the backend electronics of the DT slice test is made of boards (called AB7) hosting Virtex 7 XLXXC7VX330T-3FFG1761E FPGAs. Such boards are identical to the ones used for the DT Phase 1 upgrade, but run a dedicated firmware. Each AB7 board performs event building and runs a complete version of the DT Analytical Method TP generation algorithm. A diagram which compares the legacy architecture and the one of the DT slice test is presented in Fig. 3. In the current setup, one AB7 board is able to process information from three OBDTs. This allows to cover chambers from MB1 to MB3 with a single AB7 board. Two AB7 boards are instead used for the larger MB4, which is instrumented with four OBDTs.

Figure 5. shows example plots from the commissioning of the DT slice test. The left plot represents the cell-by-cell efficiency of finding a DT hit from the OBDT readout when one hit is found in the legacy system. At the time this plot was produced, only half of the probed MB4 chamber was equipped with OBDTs. The plot on the right shows the correlation between the position within a chamber, as computed by the offline reconstruction and by the TP generation firmware running on the AB7.

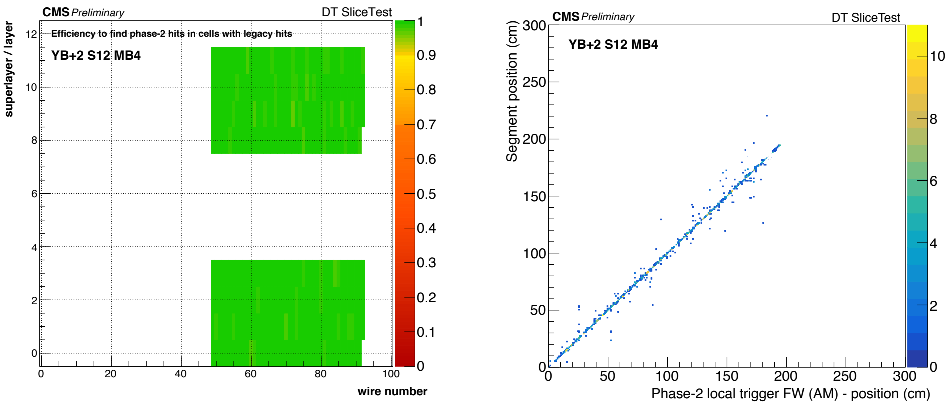

Figure 4. Cell-by-cell efficiency to find a DT hit in the DT slice test readout if a corresponding hit is recorded by the legacy readout (left) [3]. Comparison of the position within a chamber measured by the offline reconstruction and by the TP generation firmware running on an AB7 board (right) [3]

5. Summary

This report presents the studies that have been made until now to assess the DT chambers longevity under the radiation conditions expected at the HL-LHC, and the upgrade of the detector electronics planned for the DT Phase 2 upgrade. Under conservative assumptions, a fraction of the DT detector is foreseen to experience inefficiencies due to ageing. Anyhow, given the redundancy of the muon system, the impact on the overall muon reconstruction is expected to be very limited. The Phase 2 upgrade of the DT electronics architecture will allow for the design of more powerful trigger algorithms with an improved performance with respect to the legacy one. A demonstrator, including components from this new architecture, is being presently operated to gain expertise in installing, operating and commissioning the upgraded system.

References

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