Precision Muon Tracking Detectors for High-Energy Hadron Colliders

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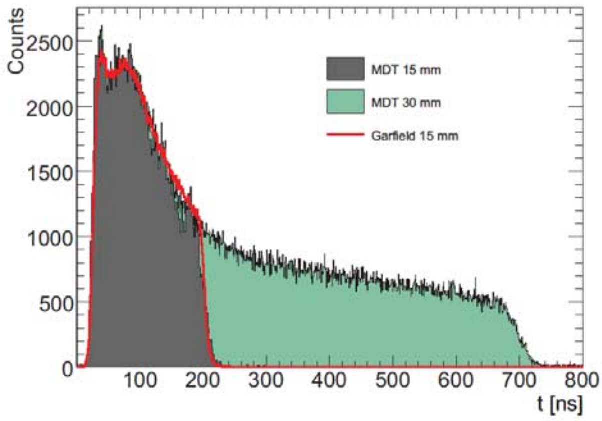
The small-diameter muon drift tube (sMDT) chambers [1] with a tube diameter of typically 15 mm (see Fig.1), half of the tube diameter of the Monitored Drift Tube (MDT) chambers in the muon spectrometer of the ATLAS detector at the LHC, are a cost-effective technology for high-precision muon tracking and trigger at the high background rates expected at high-luminosity hadron colliders, at the HL-LHC, where they are part of the upgrade program of the ATLAS detector, or at a future 100 TeV proton collider (FCC-hh). The muon spectrometers of experiments at these accelerators require precision muon tracking and a highly selective muon trigger with high efficiency and momentum resolution at high background rates.

Figure 1: Comparison of of the 15 mm and 30 mm diameter drift tubes of MDT and sMDT chambers, respectively (left) and of the corrresponding drift time spectra with 700 ns and 185 ns maximum drift time (right).



Already at the LHC design luminosity, the ATLAS muon chambers are exposed to unprecedentedly high background rates of neutrons and γ rays originating from the interactions of the proton collision products in the detector and beam shielding and have to be replaced for HL-LHC In the inner barrel and endcap layers. The background rates expected in sMDT chambers in the muon spectrometers of FCC-hh detectors at maximum luminosity are only four times higher than in the ATLAS muon spectrometer at HL-LHC. With the reduced tube diameter and therefore much shorter maximum drift time (see Fig.1), the rate capability of the sMDT chambers is increased by an order of magnitude compared to the MDTs as has been demonstrated by extensive tests in the CERN Gamma Irradiation Facility GIF. In the tests, the sMDT chambers have been operated with Ar:CO_2 (93:7) gas at 3 bar like the MDTs, With this gas, the sMDT tubes have been demonstrated to show no aging up to a charge accumulation on the sense wire of 9 C/cm, 15 times the requirement for the ATLAS MDT chambers [1]. The maximum sMDT occupancy at FCC-hh is only half of the maximum occupancy of MDT chambers in the ATLAS detector at HL-LHC (see Fig. 2).

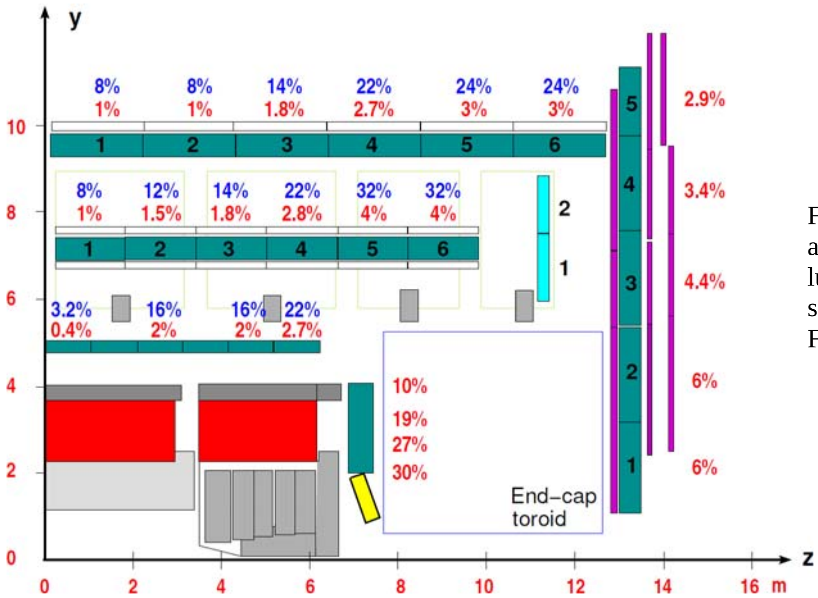


Figure 2: Expected occupancies of MDT (blue) and sMDT (red) chambers at maximum FCC-hh luminosity in a quadrant of the ATLAS muon spectrometer geometry as illustration for an FCC-hh detector.

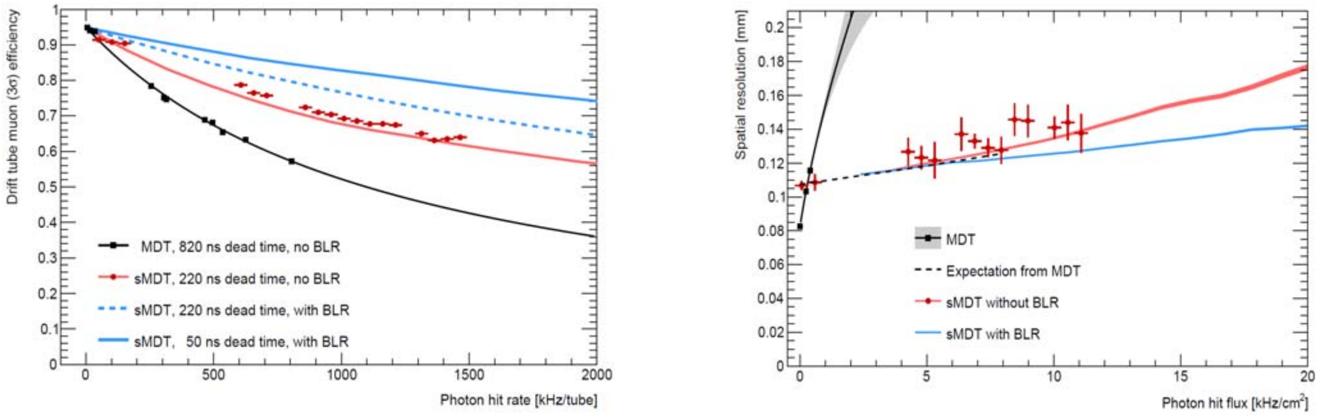


Figure 3: Left: Muon detection efficiency of MDT and sMDT drift tubes (probability to find a hit on the extrapolated muon track within 3σ of the tube spatial resolution) depending on the background hit rate for different electronics deadtime and shaping The curves are from detailed simulation of detector and electronics response (see text). Right: Spatial resolution of drift tubes depending on the background hit rate for different signal shaping (see text). The dots with error bars are measurements at the GIF, while the curves are from a full simulation of the drift tube response including readout electronics.

With the much shorter maximum drift time of the sMDT compared to the MDT tubes, the deadtime of the readout electronics can be reduced accordingly from 820 ns for the MDTs to about 200 ns or less for the sMDTs increasing the muon detection efficiency at high counting rates substantially (see Fig. 3, left). The improvement at high background rates is even larger in the spatial resolution of the drift tubes. Space charge effects leading to fluctuations in the drift time and to loss in gas gain are almost completely suppressed in sMDT tubes (see Fig. 3, right). The rate capability of the sMDT chambers . The rate capability of the sMDT chambers fulfills the requirements for the highest background regions in the ATLAS muon spectrometer at HL-LHC as well as over most of the acceptance of muon detectors at future high-energy hadron colliders. Efficiency and resolution of the sMDTs can be further improved by a considerable amount (see Fig. 3) by employing baseline restoration (BLR) in the readout electronics which suppressed signal pile-up effects as has been demonstrated with a discrete circuit emulating the MDT readout chip and adding baseline restoration (see Fig. 4).

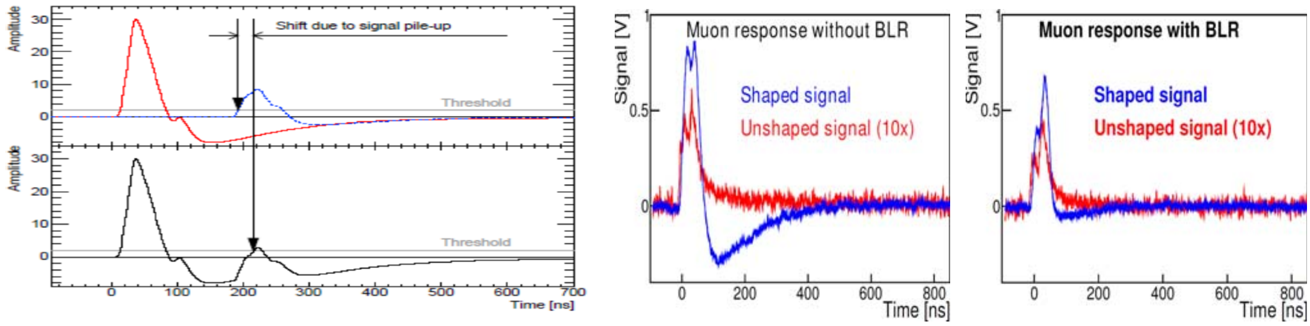


Figure 4: Illustration of signal pile-up effects (left) with bipolar shaping at high counting rates which lead to a reduction of the amplitude of successive hits and a jitter in the drift-time measurement which can be mitigated by employing baseline restoration in the readout electronics which suppresses the bipolar undershoot of the signals. Signals from an sMDT tube read out without and with baseline restoration (BLR) are shown in the middle and right graphs, respectively.

sMDT chambers are under construction for upgrades of the muon spectrometer of the ATLAS detector at high LHC luminosities. Several chambers have already been installed for LHC run II. The chamber design and construction procedures have been optimized for mass production while providing a precision of better than 10 micrometers in the sense wire positions and the mechanical stability required to cover large areas. The inherent mechanical precision allows for highly accurate monitoring of the absolute alignment of the chambers in the detector. The sMDT chamber design profits from the long experience with the MDT chambers in ATLAS and provides even higher reliability.

The ATLAS MDT precision tracking chambers will be also used in the first-level muon trigger at HL-LHC in order to improve the momentum resolution and the selectivity against the high rates of low-energy muons. The sMDT chambers will provide even better trigger performance at the high background rates in the muon systems of future colliders. Full simulation studies of the tracking and trigger performance of a muon spectrometer with sMDT chambers will be shown.

[1] H. Kroha et al., Construction and test of a full-scale prototype drift-tube chamber for the upgrade of the ATLAS muon spectrometer at high LHC luminosities, Nucl. Instr. and Meth. A718 (2013) 427.