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New High-Precision Drift-Tube Detectors for the ATLAS Muon Spectrometer

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Abstract: Small-diameter muon drift tube (sMDT) detectors have been developed for upgrades of the ATLAS muon spectrometer. With a tube diameter of 15 mm, they provide an about an order of magnitude higher rate capability than the present ATLAS muon tracking detectors, the MDT chambers with 30 mm tube diameter. The drift-tube design and the construction methods have been optimised for mass production and allow for complex shapes required for maximising the acceptance. A record sense wire positioning accuracy of 5 μm has been achieved with the new design. In the serial production, the wire positioning accuracy is routinely better than 10 μm. 14 new sMDT chambers are already operational in ATLAS, further 16 are under construction for installation in the 2019-2020 LHC shutdown. For the upgrade of the barrel muon spectrometer for High-Luminosity LHC, 96 sMDT chambers will be contructed between 2020 and 2024.

Keywords: ATLAS detector, muon detectors, drift tubes

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Contents

1 Introduction

The ATLAS Monitored drift tube (MDT) chambers [1] provide reliable muon tracking with excellent spatial resolution and high tracking efficiency independent of the track incident angle. Small-diameter muon drift tube (sMDT) chambers with a tube diameter of 15 mm, i.e. half of the tube diameter of the MDT chambers, have been developed to cope with the higher background irradiation rates at High-Luminnosity LHC (HL-LHC) and future hadron colliders and to fit into small available spaces as it is necessary for the upgrades of the ATLAS muon spectrometer. At the same time, the chamber construction methods have been optimised for mass production with significant savings in component cost, construction time and manpower compared to the ATLAS MDT chambers while providing the same reliability and mechanical robustness and even higher sense wire positioning accuracy. For the ATLAS precision muon tracking detectors a wire positioning accuracy of 20 μm (rms) is required. Standard aluminium tubes are used, with a wall thickness of 0.4 mm like for the MDT chambers. The sMDT chambers are operated in ATLAS with the same gas mixture, gas pressure and gas gain as the MDT chambers. Table 1 shows a comparison of the MDT and sMDT operating parameters. The drift time spectra are shown in the left-hand part of figure 1. The maximum drift time of the sMDT tubes is only 175 ns compared to about 720 ns of the MDT chambers leading, together with the twice smaller cross section exposed to the radiation, to about 8 times lower occupancy and a linear space-to-drift time relationship with the standard MDT drift gas Ar:CO_2 (93:7) at 3 bar pressure.

A full-scale sMDT prototype chamber of trapezoidal shape has been constructed and tested in the H8 muon beam and in the Gamma Irradiation Facility (GIF) at CERN in 2010 [4]. The chamber has been operated in the ATLAS cavern in 2012. In 2014, two sMDT chambers [5], each with two integrated RPC chambers, have been installed in access shafts in the feet region of the ATLAS barrel muon spectrometer (so-called BME chambers) and are in operation since the start of LHC run 2. In January 2017, 12 new sMDT chambers have been installed inside the detector feet in the bottom sectors of the barrel muon spectrometer (so-called BMG chambers) [6] and are in operation for the data taking in 2017.

The construction of further 16 sMDT chambers with integrated triplet RPC trigger chambers has started. They will be installed under very tight spatial constraints on the toroid magnet coils at

Table 1. Material and operating parameters of ATLAS sMDT chambers [2] compared to the MDT chambers [1].

Type	MDT	sMDT
Tube outer diameter	29.970 mm	15.000 mm
Tube wall thickness	0.4 mm	0.4 mm
Wire diameter	50 μm	50 μm
Wire pitch	30.035 mm	15.099 mm
Gas mixture	Ar:CO_2 (93:7)	Ar:CO_2 (93:7)
Gas pressure	3 bar (abs.)	3 bar (abs.)
Gas gain	$2 \cdot 10^4$	$2 \cdot 10^4$
Wire potential	3080 V	2730 V
Maximum drift time	720 ns	175 ns
Wire positioning accuracy	$< 20\ \mu$m (rms)	$< 10\ \mu$m (rms)

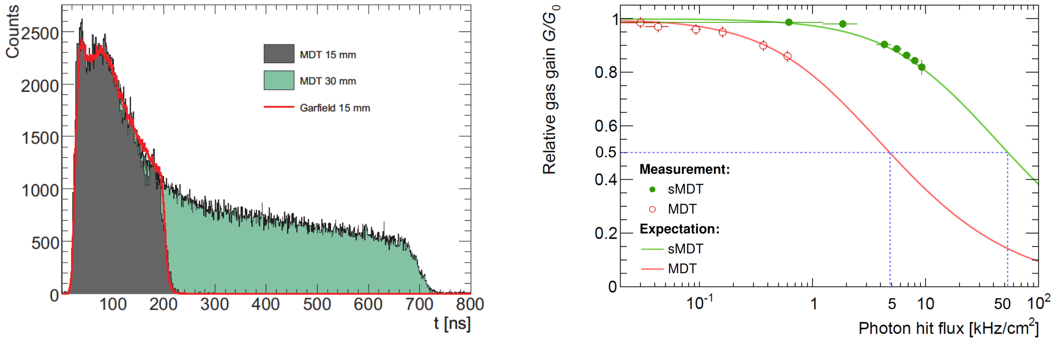

Figure 1. Left: Drift time spectra of MDT (green) and sMDT tubes (grey) together with the prediction of a GARFIELD simulation for sMDT tubes (red line) [2]. Right: Measurements of the gas gain of MDT and sMDT tubes relative to the nominal gas gain $G_0 = 20000$ as a function of the γ background rate at the Gamma Irradiation Facility at CERN compared to predictions based on the Diethorn formula [7].

the ends of the inner barrel layers (so-called BIS chambers) in the long LHC shutdown in 2019-2020 in order to improve the trigger efficiency and the rate capability of the chambers in the transition regions between barrel and endcaps. They have rather complex shapes in order to maximise the acceptance in the overlap region between the barrel part the muon spectrometer and the inner endcap layer and can only be built with the assembly methods developed for the sMDT chambers. This upgrade of the muon spectrometer serves as pilot project for the complete replacement of the MDT chambers in the by sMDT-RPC chamber modules enhancing the rate capability of the tracking and trigger chambers by about an order of magnitude and increasing the barrel muon trigger efficiency and robustness for operation at HL-LHC. The installation of new triple thin-gap RPCs of only 5 cm thickness becomes possible only by replacing the BIS MDT chmabers by sMDT chambers which have about half the height. 96 new BIS sMDT chambers will be constructed for this purpose in the years 2020-2024.

2 Performance of the sMDT chambers

The performance of MDT [3] and sMDT chambers [2] has been extensively studied at the Gamma Irradiation Facility at CERN using the existing ATLAS MDT readout electronics with bipolar shaping. For the (s)MDT amplifier-shaper-discriminator (ASD) chips at HL-LHC the same specifications will be used as for the present system. The MDT chambers can be operated up to background rates of 500 Hz/cm^2 and 300 kHz per tube. At background rates above 500 Hz/cm^2, the gas gain drops by more than 20% (see figure 1, right) leading, together with the effect of space charge fluctuations, to rapid deterioration of the spatial resolution with increasing background flux. The limitations of the MDT chambers are overcome by using drift tubes with half the diameter of the ATLAS MDT tubes while leaving the operating parameters, Ar:CO$_2$ (93:7) gas mixture at 3 bar pressure and nominal gas gain of 20000 (for a wire potential with respect to the tube wall of 2730 V in sMDT tubes), unchanged [2].

As the space charge density inside the drift tubes is proportional to the third power of the tube radius, 15 mm diameter drift tubes show a significant gain drop only at 8 times higher background rates compared to 30 mm diameter drift tubes (see figure 1, right). At the same time, the deteriorating effect of space charge fluctuations on the spatial resolution is eliminated because the drift gas is linear to good approximation for drift radii below 7.5 mm . The dependence of the average spatial resolution of MDT and sMDT drift tubes on the γ background rate is shown in figure 2. The spatial resolution deteriorates quickly with increasing background flux for the MDTs while it is affected only little by space charge effects up to very high irradiation rates for the sMDTs.

At the same background rate, the small-diameter drift tubes experience 8 times lower occupancy than the 30 mm diameter MDT tubes because of the 4 times shorter maximum drift time (see figure 1) and the twice smaller tube cross section exposed to the radiation. Because of the much shorter maximum drift time, the dead time of the MDT readout electronics (which for the MDTs is set to a nominal value of 820 ns, slightly above the maximum drift time, to prevent the detection of secondary ionization clusters) can be reduced to the minimum adjustable value of 220 ns, just above the maximum drift time of the sMDT tubes. In this way, the masking of muon hits by preceding background pulses is strongly reduced increasing the muon detection efficiency defined as the probability to find a hit on the extrapolated muon track within 3 times the drift tube resolution (3σ efficiency). Figure 2 shows the improvement of the 3σ efficiency of sMDT tubes at high background counting rates compared to the MDT tubes. Muon track segment reconstruction efficiencies of almost 100% and a spatial resolution of better than 30 μm are achieved with 8-layer sMDT chambers at the maximum background rates expected at HL-LHC.

3 Drift tube design and fabrication

The sMDT chamber design and construction procedures have been optimized for mass production while they provide highest mechanical accuracy in the sense wire positioning. Standard industrial aluminium tubes with 15 mm outer diameter and a wall thickness of 0.4 mm are used. The tubes are chromatised on the in- and outside for the cleaning purposes and reliable electrical ground contact. The ground pins are screwed into the holes between adjacent tube triplets during the glueing of the tube layers (see figure 3. The drift tubes are assembled using a semi-automated wiring station in a temperature-controlled clean room [6].

Only materials already certified for the ATLAS MDT chambers are used for sMDT drift tubes and their gas connections in order to prevent ageing. No outgassing of the plastic materials of endplugs (PBTP Crastin LW9330, reinforced with 30% glass fiber) and gas connectors (PBTP

Crastin S600F20, unreinforced) has been observed. The sMDT tubes, including the plastic material of the endplugs, have been irradiated with a 200 MBq ^{90}Sr source over a period of 4 months with a total charge accumulation on the sense wire of 9 C/cm without any sign of aging [7, 9].

Typical production rates of 100 tubes per day have been achieved with one assembly station operated by two technicians During the production of the 4300 BMG drift tubes, the failure rate of the standard drift tube quality tests of wire tension (350 ± 15 g), gas leak rate ($< 10^{-8}$ bar l/s) and leakage current (< 2 nA/m) at the nominal operating voltage of 2730 V was only 2%.

4 sMDT chamber construction and test

After passing the quality assurance tests, the drift tubes are assembled to chambers in a climatised clean room by inserting the endplug reference surfaces into a grid of fitting bores in the assembly jigs at each chamber end which define the wire positions with an accuracy of better than 5 micron and glueing them together and to the spacer and support frame using an automated glue dispenser. A complete chamber can be assembled within two working days, including the precise mounting of the global alignment sensor platforms. The same two-component expoxy glues as for the MDT chamber construction are used, Araldite 2014 between the tube layers and DP 490 between multilayers and spacer and support structures. After the glueing of each new tube layer, ground connection screws are inserted into the triangular gaps between adjacent tube layers through holes in the jig. After mounting of the gas connections, ground pins connecting to the readout and high-voltage distribution boards are screwed onto the ground screws.

Like the BME sMDT chambers, but in contrast to the BMG chambers, the BIS 7/8 and BIS 1-6 sMDT chambers will have in-plane alignment monitoring systems. The longitudinal sag monitors of the in-plane alignment system of the BIS 7/8 chambers is rotated by 180° with respect to the standard orientation parallel to the tube direction in the MDT and also the BME and BIS 1-6 chambers in order to properly monitor potential deformations of the complex shaped chambers transverse to the tubes. Two diagonal straightness monitors measure torsions between the readout and high-voltage ends in all types of chambers. Like the MDT chambers, the BME and BIS 7/8 sMDT chambers carry an optical alignment system monitoring the planarity of the chambers. The BMG and BIS sMDT chambers carry, in addition, optical sensors connecting neighboring chambers in order to monitor the planarity of a complete chamber layer in each $r\phi$ sector of the barrel muon spectrometer. This optical alignment monitoring is necessary in the so-called small barrel $r\phi$ sectors, in which also the BMG and BIS sMDT chambers are located, because these sectors are not equipped with alignment monitors connecting the three chamber layers of the large sectors of the muon spectrometer with projective light rays pointing to the interaction region. The alignment sensors are mounted on platforms which are glued to the drift-tube multilayers with 20 μm positioning accuracy with respect to the sense wires during chamber assembly using dedicated precision tools.

After the glueing of the tube layers, the positions of the individual endplug reference surfaces and, thus, of the sense wires are measured at the two chamber ends with an automated coordinate measuring machine with a precision of about 2 μm. The measurement was performed within 1-2 hours for every BME and BMG chamber and is planned as regular spot check during the BIS chamber serial production. In particular, the positions of the alignment sensor platforms with respect to the wire grid can be measured with a few micron accuracy. Sense wire positioning accuracies of better than 10 μm (rms) have been routinely achieved during BME and BMG chamber construction. An ultimate wire positioning accuracy of 5 μm (rms) has been achieved in the BMG chamber construction, which comes close the precision of the assembly jigs (see figure 3, right). All BMG sMDT chambers have a wire positioning accuracy of better than 10 μm with an average of 7 μm. After the measurement, the individual wire positions are known with 2 μm accuracy.

After the wire position measurement, the parallel gas distribution system is mounted, consisting of modular injection molded plastic gas connectors connecting tubes in columns perpendicular to the chamber plane to the chromatised aluminium gas distribution bars (see figures 3, left, and 4). Gas leak rates at 3 bar pressure below the limit of $2n \cdot 10^{-8}$ bar l/s required for a chamber with n tubes have been achieved for all BMG chambers. After the installation of the gas distribution system, ground pins and Faraday cages, the high-voltage and the signal distribution boards as well as the active readout electronics (mezzanine) cards with 6 x 4 channels matching the transverse

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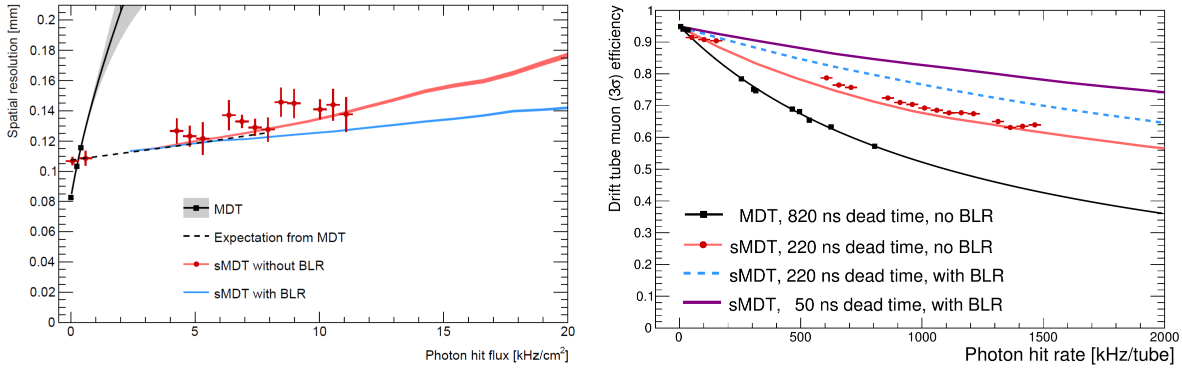

Figure 2. Average spatial resolution (left) and muon detection efficiency (within 3σ of the reconstructed track) of MDT and sMDT drift tubes measured at the Gamma Irradiation Facility at CERN as a function of the γ background rate using standard MDT readout electronics with bipolar shaping. The same front-end electronics scheme and parameters will be used for MDT and sMDT chambers at HL-LHC. Further improvement of the sMDT drift tube spatial resolution at high background rates and space charge densities can be achieved by employing additional fast baseline restoration (BLR) in order to suppress signal pile-up effects (blue curves) [8] which is not needed for operation at HL-LHC.

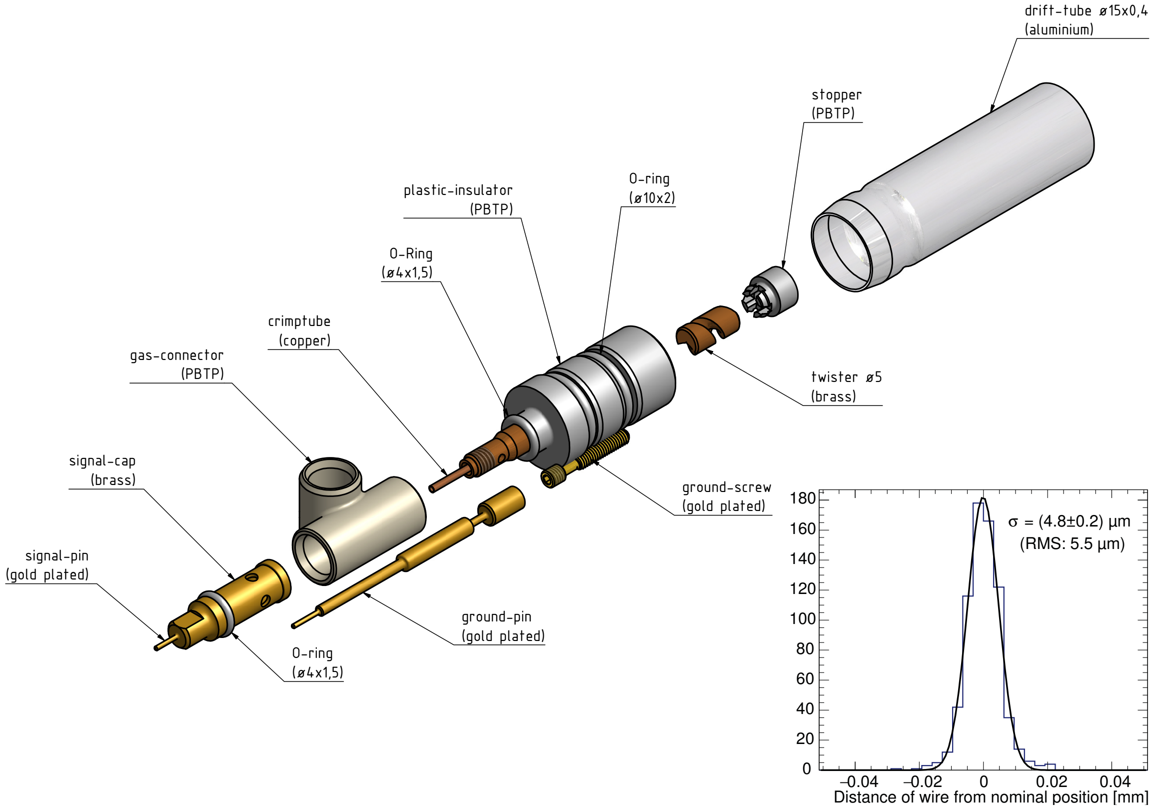

Figure 3. Left: Cross section of an sMDT endplug with internal wire locator and external reference surface for tube and wire positioning during construction and for wire position measurement. Right: Residuals of the sense wire positions measured at both ends of a BMG sMDT chamber with 356 tubes with respect to the nominal wire grid. The width of the distribution includes the accuracy of the coordinate measureing machine of about 2 μm.

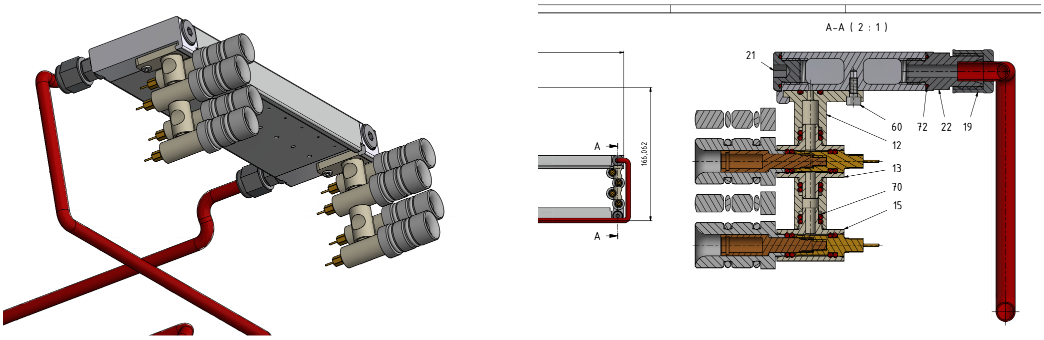

Figure 4. Schematics of the sMDT chamber gas distribution system.