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# Construction and Test of a Prototype Chamber for the Upgrade of the ATLAS Muon Spectrometer

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**Abstract**

Monitored drift tube chambers are used as precision tracking detectors in the muon spectrometer of the ATLAS experiment at the LHC at CERN. These chambers provide a spatial resolution of 35 μm and a tracking efficiency of close to 100 % up to background rates of 0.5 kHz/cm$^2$, the former being limited at higher rates mainly due to space-charge effects and the latter due to the maximum drift time of 700 ns. For LHC upgrades, a faster drift tube chamber has been developed, using drift tubes with a diameter of 15 mm instead of 30 mm. The increased channel density and shorter drift time of about 200 ns raise the rate capability to about 10 kHz/cm$^2$, while retaining the spatial resolution. A prototype chamber with trapezoidal shape consisting of $2 \times 8$ layers of 15 mm diameter drift tubes with an active surface of 0.8 m$^2$ has been constructed. The prototype chamber has been tested at CERN with a 180 GeV muon beam at a SPS beam line and with cosmic ray muons at the Gamma Irradiation Facility (GIF) at high $\gamma$ radiation rates.

*Keywords:* drift tubes, muon chambers, ATLAS, LHC

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## 1. Introduction

The muon detectors of the experiments at the Large Hadron Collider (LHC) will encounter unprecedentedly high background counting rates due to neutrons and $\gamma$ rays in the energy range up to about 10 MeV. These particles originate mainly from secondary interactions of the hadronic collision products with accelerator elements, shielding material and the detector components. The LHC schedule foresees a continuous increase of the luminosity eventually exceeding the original design value of $10^{34}$ cm$^{-2}$ s$^{-1}$. Assuming that the background rates approximately scale with the luminosity, the rate capability of the muon detectors will be exceeded. The Monitored Drift Tube (MDT) chambers in the muon spectrometer of the ATLAS detector at the LHC [1? ], for example, are designed to cope with counting rates of up to about 300 kHz in the endcap regions of the spectrometer corresponding to an occupancy of 21%.

The MDT chambers consist of two triple or quadruple layers (multilayers) of aluminum drift tubes of 30 mm outer diameter and 0.4 mm wall thickness filled with Ar:CO$_2$ (93:7) gas mixture at an absolute

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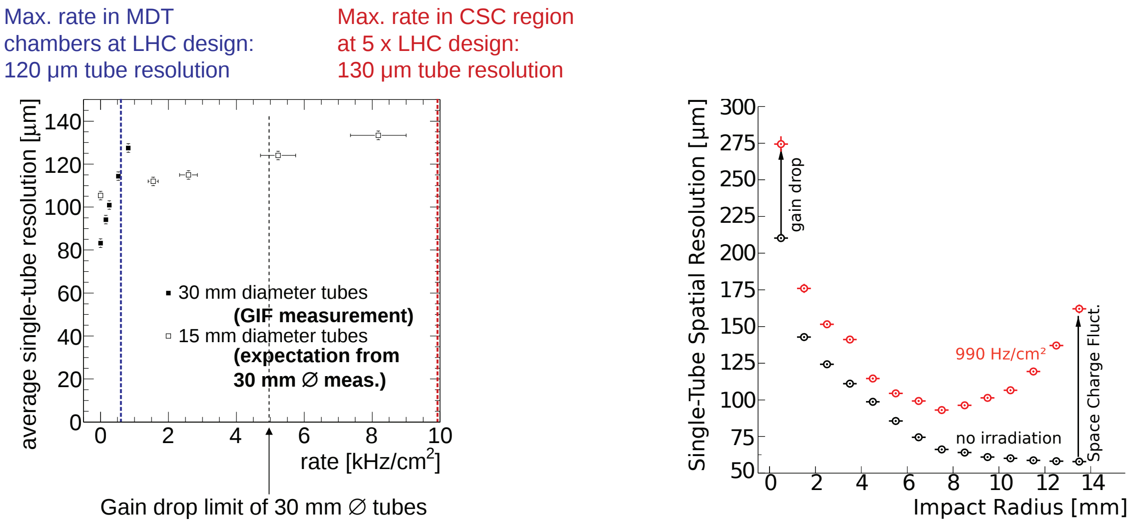


(a) (b)

Fig. 1: Average spatial drift tube resolution as a function of the background counting rate in 15 mm and 30 mm diameter tubes (a) and spatial resolution as a function of the impact radius for tubes which were irradiated with a $\gamma$ flux of 990 Hz/cm$^2$ compared to non-irradiated tubes (b).

pressure of 3 bar. A voltage of +3080 V is applied between the 50 µm diameter gold plated W-Re anode wire and the tube wall, leading to a gas gain of $2 \cdot 10^4$ and a maximum drift time of about 700 ns. The average spatial resolution of individual drift tubes is 80 µm at low counting rates [4]. With a sense-wire positioning accuracy of better than 20 µm, this translates to a chamber spatial resolution of 35 µm.

At the LHC design luminosity of $\mathcal{L} = 10^{34}$ cm$^{-2}$ s$^{-1}$, the highest background rate in the MDT chambers is expected to be about 0.1 kHz/cm$^2$ in the inner endcap layers closest to the beam pipe [3]. As the knowledge about showering processes in the absorber, chamber sensitivity to different kind of particles, cross-sections and particle multiplicities is still limited and solely based on simulation, a safety factor of five is taken into account. Hence the MDT chambers are designed to cope with particle fluxes of up to 0.5 kHz/cm$^2$ corresponding to maximum counting rates of about 200–270 kHz in the 1.3–1.8 m long drift tubes of the inner forward chambers.

The LHC upgrade schedule foresees a continuous luminosity increase fist to two times, later up to five times the design luminosity. Assuming that the background rates will scale linear with the instantaneous luminosity, the degradation of the MDT performance will compromise the ATLAS physics goals.

We investigate the possibility of using drift tubes with smaller tube diameter and thus shorter maximum drift time in the regions of highest background radiations of the muon detectors of the LHC experiments. Building on the experience with the ATLAS MDT chambers, new muon drift tube detectors with 15 mm diameter tubes have been developed which can cope with 10 times higher particle fluxes.

## 2. Drift Tube Performance at High Counting Rates

At high counting rates, the drift tubes of the ATLAS MDT chambers are known to suffer from a degradation of the spatial resolution due to space-charge effects (see Fig. 1) [5, 6] and of the muon detection efficiency due to the increased drift tube occupancy (see Fig. 6) [4]. Both effects can be supressed by reducing the tube diameter while leaving the other operating parameters of the drift tubes, in particular gas mixture, pressure and gas gain, unchanged.

Decreasing the outer drift tube diameter from 30 mm to 15 mm and the operating voltage from 3080 to 2730 V leads to a reduction of the maximum drift time by a factor of 3.5 from about 700 ns to 200 ns [7]. In addition, the background counting rate, dominated by the conversion of the neutron and gamma radiation in

Table 1: Maximum background counting rate and occupancy of 15 and 30 mm diameter drift tubes for different luminosities at the innermost radius of the Small Wheel (0.55 m tube length) including a safety factor of 5.

| | | 15 mm ⌀ tubes | | 30 mm ⌀ tubes |
|---|---|---|---|---|
| Luminosity ($\mathrm{cm^{-2}s^{-1}}$) | Background flux ($\mathrm{kHz/cm^2}$) | Counting Rate in 0.55 m long tubes (kHz/tube) | Occupancy of 0.55 m long tubes (%) | Occupancy of 0.55 m long tubes (%) |
| $1\times10^{34}$ | 2.0 | 165 | 3.3 | 23 |
| $2\times10^{34}$ | 4.0 | 330 | 6.6 | 46 |
| $5\times10^{34}$ | 10.0 | 825 | 16.5 | 100 |

the tube walls, decreases proportional to the tube diameter, i.e. by a factor of two per unit tube length. Both effects together lead to a reduction of the occupancy by about a factor of 7. Even in the area with highest expected background rates in the inner layer of the very forward region of the ATLAS muon spectrometer (in the pseudorapidity range $2.0 < |\eta| < 2.7$), where currently cathode strip chambers are installed, the occupancy stays below 17 % for 0.56 m long 15 mm diameter drift tubes at counting rates up to 8.5 $\mathrm{kHz/cm^2}$ or about 800 kHz per tube, corresponding to five times LHC design luminosity (see Table 1). At the same time, at least twice the number of drift tube layers can be accommodated in the same detector volume allowing for additional improvement of the muon detection efficiency, spatial resolution and redundancy in terms of pattern recognition.

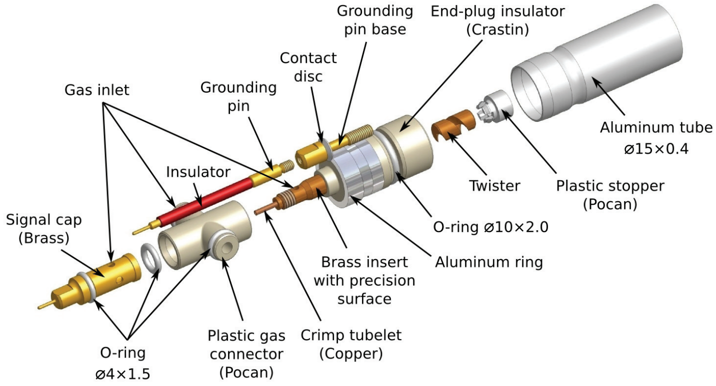
At high counting rates, the space-charge generated by the ion clouds drifting towards the tube wall lowers the electric field strength near the anode wire leading to a reduction of the gas gain. The resulting loss in signal height and, therefore, spatial resolution grows with the inner tube radius $R_2$ proportional to $R_2^3 \cdot \ln(R_2/R_1)$ [8] where $R_1 = 25$ μm is the wire radius. Therefore, the signal height reduction due to space charge is 10 times smaller in 15 mm compared to 30 mm diameter tubes. Fluctuations of the space charge and, consequently, of the electric field in the tube lead to variations of the drift velocity in non-linear drift gases like $Ar{:}CO_2$ (93:7) causing a deterioration of the spatial resolution which increases rapidly with the drift distance above a value of about 7.5 mm [5, 6]. In addition, the space-to-drift time relationship for the $Ar{:}CO_2$ (93:7) drift gas is more linear at drift distances below 7.5 mm reducing the sensitivity of the position measurement to environmental parameters such as gas composition and density, magnetic field and, in particular, irradiation rate.

Since the drift tube spatial resolution at low background rates improves with the drift distance, the average single-tube resolution deteriorates from 80 μm for 30 mm diameter tubes [4, 6] to about 105 μm for 15 mm diameter tubes. For 30 mm diameter drift tubes, the resolution has been measured to deteriorate approximately linearly with the counting rate to about 120 μm at 500 $\mathrm{Hz/cm^2}$ [4, 6]. For 15 mm diameter tubes, the rate dependence of the resolution, dominated by the gain drop effect, is expected to be about 10 times smaller (see Fig. 1a).

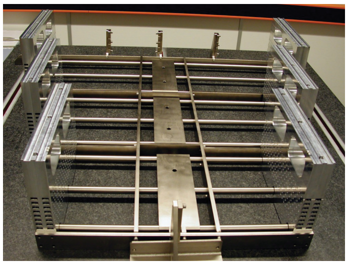
## 3. Chamber Design and Fabrication

A full-scale prototype chamber with 15 mm diameter drift tubes has been constructed following as close as possible the current ATLAS MDT chamber design. The prototype has a trapezoidal shape with three different tube lengths of 560, 760 and 920 mm, arranged in 2 × 8 layers with 72 drift tubes each. The chamber dimension corresponds to the current size of cathode strip chambers being installed in the inner forward regions of the ATLAS muon spectrometer closest to the beam pipe. The challenge for the new chamber design is the four times denser tube package, compared to the MDT chambers with 30 mm drift tubes, with corresponding gas and electrical connections to the individual tubes.

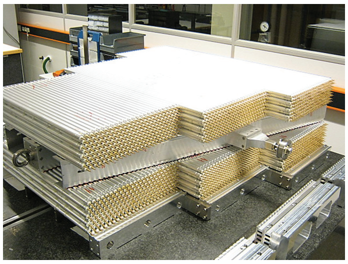
Central to the chamber design is the newly developed tube end-plug (Fig. 2a) which insulates the sense wire from the tube wall, centers the wire in the tubes and provides high-voltage-safe connections to the



(a) Exploded view of the endplug for 15 mm diameter drift tubes with interfaces to the gas distribution and the electronics boards. The spiral-shaped wire locator (twister) with 50 μm inner diameter fits into the central bore of the brass insert (the arrow points to the external reference surface for precise wire positioning in the chamber).



(b) The assembly jigs for precise gluing of the multilayers.



(c) Glued drift tube chamber with spacer frame.

Fig. 2: Drift tube and chamber assembly.

gas distribution manifolds, the readout and high-voltage distribution boards (Fig 3). Ground pins inserted between adjacent tubes electrically interconnect the tube walls and connect them to ground. The tubes are assembled to a chamber using precise mechanical jigs (see Fig. 2b) positioning the sense wires relative to each other with better than 20 μm accuracy.

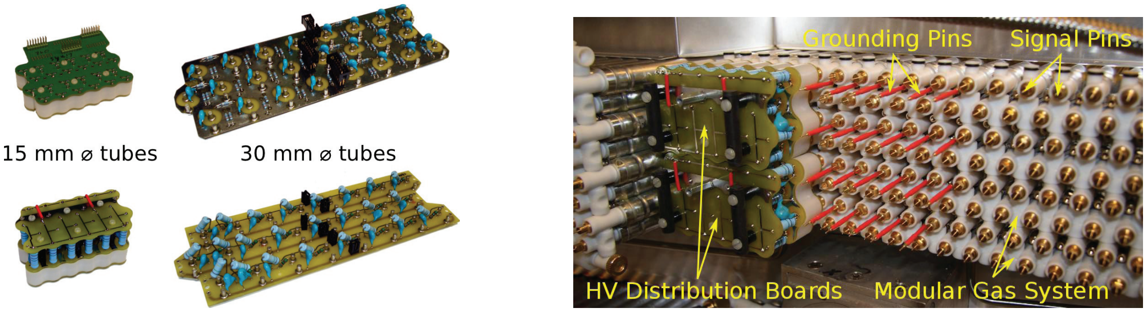
New electronics boards for high-voltage supply and signal extraction have been developed (see Fig. 3). The major challenge is the high-voltage stability with the little space available. A three-dimensional layout of the boards was chosen to cope with the four times higher channel density compared to the 30 mm diameter drift tubes. One board connects directly to the signal and grounding pins of 24 drift tubes.

## 4. Test Results

The chamber was equipped with the newly developed passive front-end boards for high-voltage distribution and signal extraction, while using the ATLAS MDT active readout electronics comprising signal amplifiers and shapers, TDC, ADC etc. [2]. No HV-trips have been observed during an operational time of several weeks with leakage currents of about 1.5 nA per tube.

The chamber performance has been tested with a 180 GeV muon beam at CERN with low background radiation. It total several tens of millions events have been recorded at different incident angles between 0 and 30°. Fig. 4a shows the chamber installed in the rotating support frame, equipped with a scintillator for triggering on the beam muons. The average single tube resolution was measured to be 122.7 ± 5.6 μm and agrees well with the resolution of the 30 mm diameter tubes for impact radii up to 7.1 mm (see Fig. 5a). An additional improvement of the drift tube resolution by up to 20 μm can be achieved by correcting the drift time measurements for the time slewing [4] leading to a spatial resolution of the chamber of about 35 μm at low counting rates. For the expected highest counting rates of 14 kHz/cm$^2$ (including a safety factor of 4) , the chamber resolution is predicted to stay below 50 μm fulfilling the ATLAS physics goals even for five times the LHC design luminosity.

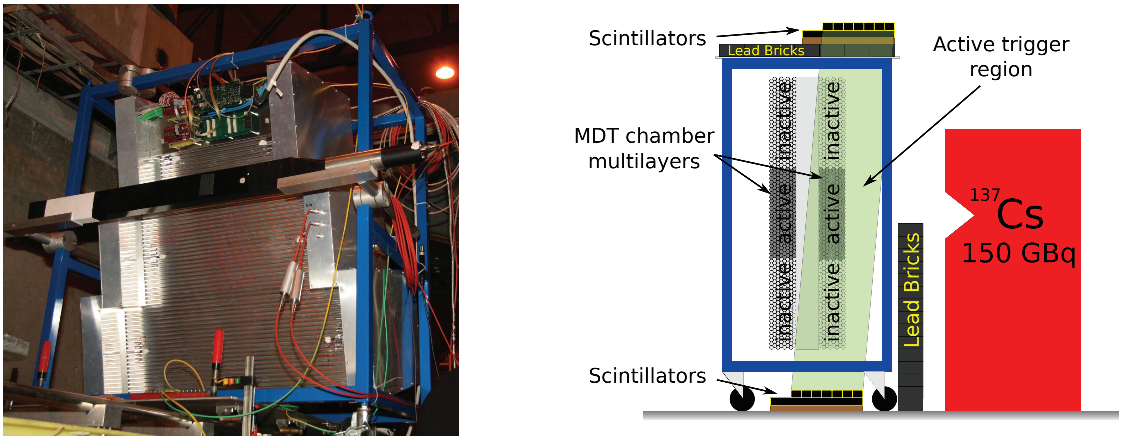
The same chamber has been tested with cosmic ray muons in the Gamma Irradiation Facility (GIF) at CERN at $\gamma$ counting rates of up to 1.2 MHz per tube. The chamber was installed as close as possible to the $\gamma$



(a) Read-out (top) and high-voltage distribution (bottom) front-end boards for 15 mm and 30 mm diameter drift tubes.

(b) Two high-voltage distribution boards mounted on the drift tubes. Also visible are signal and grounding pins and parts of the modular gas distribution system.

Fig. 3: Photographs of the high-voltage distribution and read-out front-end boards



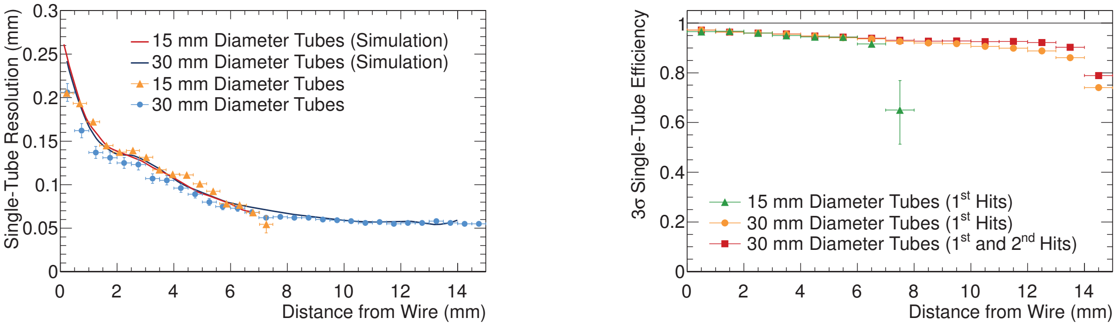
(a)

(b)

Fig. 4: Measurement setups (a) in a high energy muon beam at a SPS beam line and (b) at the Gamma Irradiation Facility at CERN. Scintillator detectors were used in both configurations for triggering on the beam and cosmic muons, respectively.

source to get high counting rates (see Fig. 4b). The lower part of the chamber was shielded from the source so it could be used to find and reconstruct good muon tracks. An additional layer of lead was added directly below the upper scintillator layer to reduce the number of low energy muons which are strongly subject to multiple scattering in the aluminum tube walls.

With increasing background counting rate, the muon hits are increasingly masked by background hits. The measured probability to detect a muon hit at the drift radius expected within three times the spatial drift tube resolution of the extrapolation from the shielded reference part is shown in Fig. 6 as a function of the counting rate in comparison with previous measurements for 30 mm diameter drift tubes with the same readout electronics [4]. The drift tube efficiency is considerably increased as expected, approximately by the ratio of the sums of the maximum drift time and the electronics dead time which was set to 700 ns and 200 ns for the 30 mm and 15 mm diameter tubes, respectively.



(a) (b)

Fig. 5: The spatial resolution (a) and muon detection efficiency (b) of 15 and 30 mm diameter drift tubes as a function of the impact radius.

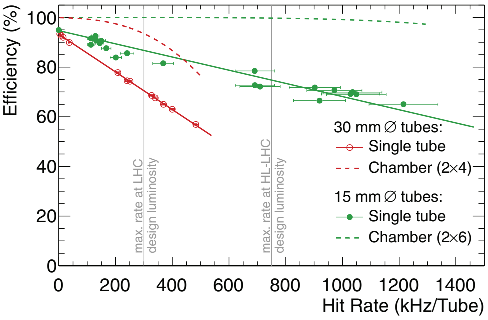


Fig. 6: Muon detection efficiency (see text) of 15 and 30 mm diameter drift tubes as a function of the $\gamma$ ray background counting rate.

## 5. Conclusions

Monitored drift tube chambers are a proven and well tested technology for high counting rates. Reducing the drift tube diameter to 15 mm improves the rate capability further and makes the detector sufficiently fast to cope with the counting rates expected in the forward regions of the ATLAS muon spectrometer under worst background conditions at the LHC with five times increased instantaneous luminosity. A full-scale prototype chamber with 1,152 drift tubes with 15 mm diameter was designed, assembled and extensively tested.

## References

[1] The ATLAS collaboration, Technical Design Report for the ATLAS Muon Spectrometer, CERN/LHCC 97-22, May 1997.
[2] Y. Arai et al., ATLAS Muon Drift Tube Electronics, JINST 3 P09001 (2008).
[3] S. Baranov et al., Estimation of Radiation Background, Impact on Detectors, Activation and Shielding Optimization in ATLAS, ATLAS internal note, CERN-ATL-GEN-2005-001 (2005).
[4] S. Horvat et al., Operation of the ATLAS Precision Muon Drift-Tube Chambers at High Background Rates and in Magnetic Fields, IEEE Trans. on Nucl. Science Instr., Vol. 53, No. 2 (2006) 562.
[5] M. Aleksa et al., Rate Effects in High-Resolution Drift Chambers, Nucl. Instr. and Meth. A 446 (2000) 435.
[6] M. Deile et al., Performance of the ATLAS Precision Muon Chambers under LHC Operating Conditions, Nucl. Instr. and Meth. A518 (2004) 65.
[7] B. Bittner et al., Development of Muon Drift-Tube Detectors for High-Luminosity Upgrades of the Large Hadron Collider, Nucl. Instr. and Meth. A (2009), doi:10.1016/j.nima.2009.06.086.
[8] W. Riegler, High Accuracy Wire Chambers, Nucl. Instr. and Meth. A494 (2002) 173.

[9] F. Bauer et al., Construction and Test of the Precision Drift Chambers for the ATLAS Muon Spectrometer, IEEE Trans. on Nucl. Science Instr., Vol. 48, No. 3 (2001) 302; F. Bauer et al., The First Precision Drift Tube Chambers for the ATLAS Muon Spectrometer, Nucl. Instr. and Meth. A478 (2002) 153.

[10] O. Biebel et al., Test and calibration of large drift tube chambers with cosmic rays, IEEE Trans. on Nucl. Science Instr., Vol. 52 (2005) 2998.

[11] J. Dubbert et al., Precision Drift Tube Chambers for the ATLAS Muon Spectrometer at Super-LHC, proceedings of the 2008 IEEE Nuclear Science Symposium, Dresden, Germany, 19-25 October 2008, Nuclear Science Symposium Conference Record 2008, IEEE, 2008, MPI report, MPP-2008-191, November 2008.