Performance of Fast High-Resolution Muon Drift Tube Chambers for LHC Upgrades

S. Adomeit*, O. Biebel*, B. Bittner†, J. Dubbert†, A. Engl*, R. Hertenberger*, M. Kilgenstein†, O. Kortner†, S. Kortner†, H. Kroha†, F. Legger†, J. v. Loeben†, F. Rauscher*, R. Richter†, P. Schwegler†, A. Zibell*
*Ludwig-Maximilians-Universität München, Am Coulombwall 1, D-85748 Garching, Germany
†Max-Planck-Institut für Physik, Föhringer Ring 6, D-80805 München, Germany

***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 2×8 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 (H8) and with cosmic ray muons at the Gamma Irradiation Facility (GIF) at high γ radiation rates.**

***Index Terms*—muon chamber, drift tube, LHC upgrade**

I. Introduction

THE muon detectors of the experiments at the Large Hadron Collider (LHC) will encounter background counting rates due to neutrons and γ rays in the energy range up to about 10 MeV on an unprecedented scale. They originate mainly from secondary interactions of the hadronic collision products with accelerator elements, shielding material and detector components. The LHC schedule foresees a continuous increase of the luminosity eventually exceeding the original design value of $10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The Monitored Drift-Tube (MDT) chambers in the muon spectrometer of the ATLAS detector at the LHC [1], [2], for example, are designed to cope with a maximum counting rate of about 300 kHz in the drift tubes of the inner forward chambers, corresponding to an occupancy of 21%.

An MDT chamber consists of up to 432 aluminum drift tubes, arranged in 2×3 or 2×4 tube layers, of 30 mm outer diameter with 0.4 mm wall thickness filled with Ar:CO_2 (93:7) gas mixture at 3 bar absolute pressure. A voltage of +3080 V is applied between a 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 spacial resolution of individual drift tubes of 80 μm at low counting rates [3] together with a sense-wire positioning accuracy of 20 μm translates to a total chamber spacial resolution of 35 μm.

At the LHC design luminosity of $\mathcal{L} = 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, 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 [4]. As the knowledge about showering processes in the absorber, chamber sensitives 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.

II. Drift-tube performance at high rates

THE performance of the drift tubes of the MDT chambers is known to decrease at high counting rates. Space charge effects [5], [7] are degrading the resolution of the single drift-tubes and the muon detection efficiency due to the increased drift tube occupancy [3]. Both effects can be suppressed by reducing the tube diameter while leaving the other operational parameters of the detector, in particular gas mixture, pressure and gain, unchanged.

Decreasing the outer drift tube diameter from 30 mm to 15 mm the maximum drift time is reduced by a factor of 3.5 from 700 ns to 200 ns [7] (see Fig. 1), while keeping the gas gain constant at about $2 \cdot 10^4$ by lowering the operating voltage from 3080 V to 2730 V. As the background counting rate decreases proportional to the tube diameter, i.e. by a factor of two per unit tube length, the occupancy is reduced by about factor of 7 in total. 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

F. Legger is now at Ludwig-Maximilians-Universität München, Germany
J. v. Loeben is the corresponding author (joerg.von.loeben@mpp.mpg.de)

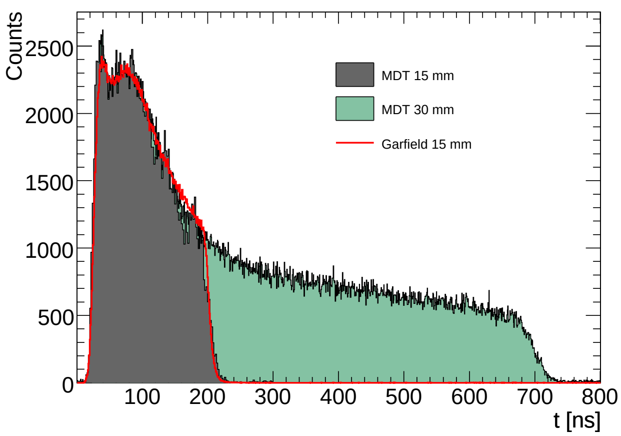


Fig. 1. Drift time spectra of 30 mm and 15 mm diameter drift tubes operated with Ar:CO_2 (93:7) gas mixture at bars absolute pressure and a gas gain of 2×10^4. The measurement with cosmic ray muons is compared to Garfield [8] simulations for the 15 mm diameter tubes.

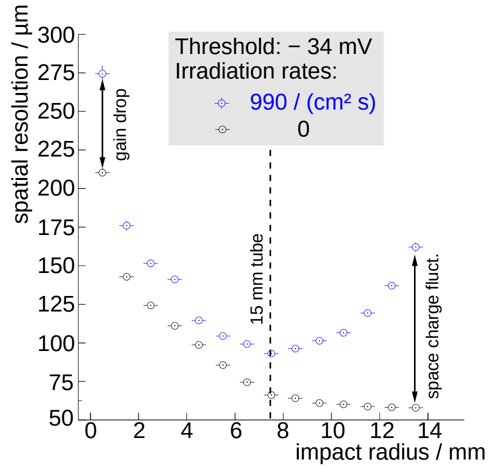


Fig. 2. Spatial resolution of a 30 mm diameter drift tube as a function of the drift distance for two different background rates.

$2.0 < |\eta| < 2.7$), where currently cathode strip chambers are installed, the occupancy stays below 15 % for 0.56 m long 15 mm diameter drift tubes at counting rates up to 8.5 kHz/cm^2 or about 700 kHz per tube, corresponding to five times LHC design luminosity. In addition, about twice the number of drift tube layers can be accommodated in the same active detector volume allowing for additional improvement of the muon detection efficiency, spatial resolution and redundancy in terms of pattern recognition. A first verification of the expected increase of detection efficiency has been obtained up to rates of about 300 kHz per tube at the CERN Gamma Irradiation Facility [9].

At high counting rates, the space charge created by the ionizing radiation in the drift tubes lowers the effective potential near the anode wires. As a consequence, the gas gain is reduced leading to a reduction of the spatial resolution of the drift tubes near the sense wires. This gain drop effect is proportional to $R_2^3 \cdot \ln(R_2/R_1)$ [10] where R_2 denotes the inner tube radius and $R_1 = 25\,\mu$m the radius of the anode wire. Hence, the signal reduction is 10 times smaller in 15 mm compared to 30 mm drift tubes. In addition, the fluctuations of the space-charge lead to fluctuations of the electric field in the tubes. Since the drift velocity depends on the electric field in non-linear drift gases like Ar:CO_2, this causes a deterioration of the spacial resolution, which increases rapidly with the drift distance above a value of 7.5 mm [5], [11]. Fig. 2 shows the degradation of the spatial resolution of the individual drift tubes as a function of the drift distance with increasing counting rates, measured with 30 mm drift tubes. An additional advantage is the higher linearity of the space-to-drift time relationship for the Ar:CO_2 (93:7) drift gas 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-

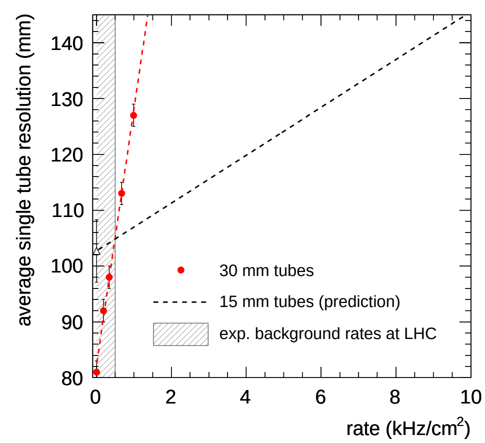


Fig. 3. Average spatial drift tube resolution as a function of the background counting rate as measured in 30 mm and predicted for 15 mm diameter tubes.

tube resolution deteriorates from $80\,\mu$m for 30 mm diameter tubes [3], [5] to about $100\,\mu$m 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 $100\,\mu$m at 500 Hz/cm^2 [3], [5]. 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. 3).

III. The Prototype Chamber

A full-scale prototype chamber with 15 mm diameter drift tubes has been constructed [6] following as much 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

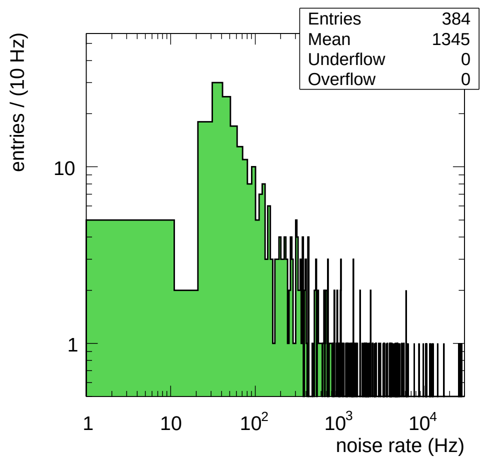
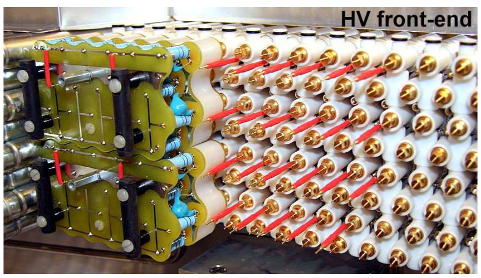
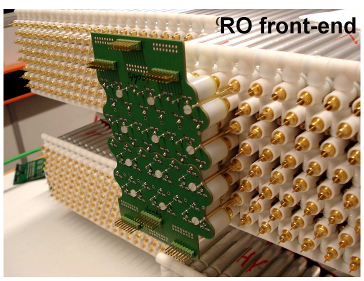


Fig. 4. Measured noise rate of the 384 readout channels (one third of the prototype chamber) for a threshold of 32 mV.



(a)



(b)

Fig. 5. Photograph of the (a) high-voltage distribution front-end boards and (b) the interface boards between the drift-tubes and the active readout electronics.

electrical connections to the individual tubes. Central to the chamber design is the newly developed tube end-plug which insulates the sense wire from the tube wall, centers the wire in the tubes and provides high-voltage-safe connections to the gas distribution manifolds, the readout and high-voltage distribution boards. Ground pins inserted between adjacent tubes electrically interconnect the tube walls and connect them to the ground. The tubes are assembled to a chamber using precise mechanical jigs positioning the sense wires relative to each other with better than 20 μm accuracy.

IV. Test Results

FOR the first measurements, one third of the chamber (384 tubes) was equipped with newly developed passive readout and high-voltage distribution boards (see Fig. 5), while

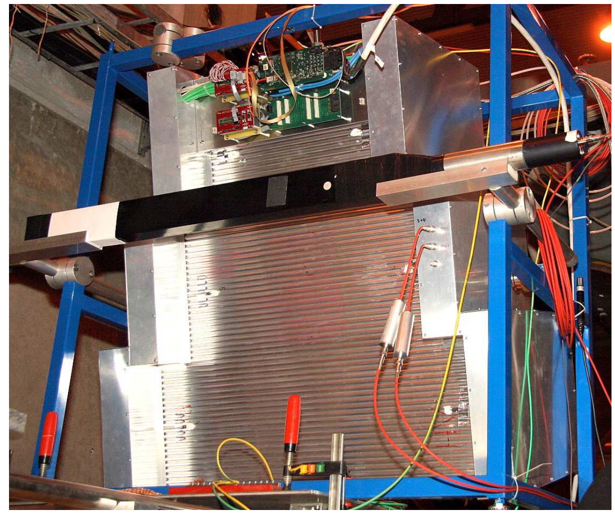


Fig. 6. The prototype chamber with 15 mm diameter drift tubes at the H8 test beam at CERN.

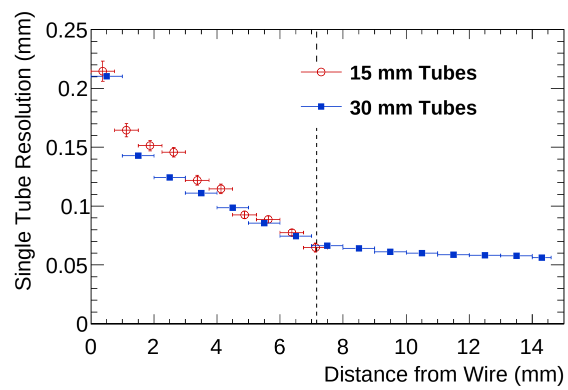


Fig. 7. Drift tube resolution of 15 mm and 30 mm diameter measured without background radiation.

using the ATLAS MDT active readout electronics [2]. No HV-trips have been observed during a operational time of several weeks with leakage currents of about 1.5 nA/tube. The noise-rate, as shown in Fig. 4, is measured to be less than 400 Hz for 90 % of the readout channels using a threshold of 32 mV.

The chamber performance has been tested with a 180 GeV muon beam at CERN (H8) with low background radiation. It total about $27 \cdot 10^6$ events have been recorded at different incident angles between $0°$ and $30°$. Fig. 6 shows the chamber installed in the rotational support frame, equipped with a scintillator for triggering on the beam muons. The average single tube resolution was measured to $122.7 \pm 5.6\,\mu$m and agrees well with the resolution of the 30 mm diameter tubes for impact radii up to $7.1\,\mu$m (see Fig. 7). An additional improvement of the drift tube resolution by up to $20\,\mu$m can be achieved by correcting the drift time measurements on the slewing time [3] leading to a spatial resolution of the chamber of about $35\,\mu$m at low counting rates. For the expected highest counting rates of 8.5 kHz/cm^2, the chamber resolution is predicted to stay below $40\,\mu$m fulfilling the ATLAS physics goals even for five times the LHC design luminosity.

V. Conclusions

DRIFT TUBE detectors provide robust and efficient tracking at high background counting rates expected in the muon detectors of the LHC experiments, in particular the ATLAS detector. Drift tubes with 15 mm diameter are 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 1152 drift tubes has been designed, assembled and successfully tested.

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