Precision Drift-Tube Chambers for the ATLAS Muon Spectrometer at Super-LHC

O. Kortner, H. Kroha, F. Legger, R. Richter,
Max-Planck-Institut für Physik, Föhringer Ring 6, D-80805, München, Germany,
A. Engl, R. Hertenberger, F. Rauscher,
Ludwig-Maximilians-Universität München, Am Coulombwall 1, D-85748, Garching, Germany,

***Abstract*—The measurement of muon momenta with very high precision is one of the most challenging aspects of the ATLAS experiment at the Large Hadron Collider (LHC) at Cern. The ATLAS muon detector is equipped with three layers of Monitored Drift Tube (MDT) chambers in a magnetic field generated by a superconducting air-core magnet system for precision tracking and is designed to withstand particle fluxes of up to 500 cm^{-2}s^{-1}. However 10 times higher background rates are to be expected at the Super-LHC, the luminosity upgrade of the LHC. We investigate the possibility of improving the performances of the MDT chambers at high rates by reducing the diameter of the drift tubes from 30 to 15 mm. We report on the results of cosmic ray measurements with a prototype detector equipped with the thinner drift tubes in particle fluxes of up to 1400 cm^{-2}s^{-1}.**

I. Introduction

LARGE Monitored Drift-Tube (MDT) chambers in a toroidal magnetic field generated by superconducting air-core magnets are used for precision tracking in the muon spectrometer of the ATLAS detector at the Large Hadron Collider (LHC) at CERN [1]. The MDT chambers are equipped with two triple or quadruple layers of pressurized aluminum drift tubes of 30 mm diameter and 0.4 mm wall thickness, filled with an Ar:CO_2 (93:7) gas mixture at an absolute pressure of 3 bar. An operating voltage of 3080 V, corresponding to a 2 x 10^4 gas gain, is applied to the 50 μm diameter gold-plated tungsten-rhenium wire, which is positioned at the center of the tube with an accuracy of 20 μm. The single tube spatial resolution is 80 μm, which translates into a position resolution of 30 μm for a 6-layer chamber. This allows for the measurement of muon momenta up to 1 TeV/c with a resolution of better than 10% [2].

The main background in the ATLAS muon spectrometer consists in photons and neutrons in the 1 MeV range, mainly originated in secondary interactions of hadronic collision products with the forward calorimeter, shielding material, beam pipe and machine elements. Detection efficiencies in the MDT chambers are typically $\sim$1% for photons and $\sim$0.1% for neutrons [3]. The highest background rate predicted by Monte Carlo simulations in the ATLAS muon spectrometer at the LHC design luminosity of 10^{34}cm^{2}s^{-1} is 100 cm^{-2}s^{-1} in the inner forward layers [4]. Due to limited knowledge of the showering process in the absorber, chamber sensitivities, proton-proton cross section and particle multiplicity in primary collisions at the LHC center-of-mass energy, $\sqrt{s} = 14$ TeV, a safety factor of 5 has been considered in the design of the ATLAS muon spectrometer. Hence the MDT chambers are designed to cope with particle fluxes up to 500 cm^{-2}s^{-1}, which corresponds to a counting rate of 300 kHz/tube for 2 m long tubes.

The LHC upgrade schedule foresees an increase of the luminosity of an order of magnitude beyond the nominal value of 10^{34}cm^{2}s^{-1} [5]. If the background rates scale with the luminosity, the degradation of the performaces of the MDT chambers will compromise ATLAS physics goals. In this letter, we investigate the possibility of replacing the current MDT chambers in the hottest region of the muon spectrometer with new chambers equipped with smaller diameter drift tubes.

Manuscript received November xx, 2008.

II. High rate effects on MDT chamber performances

At high background rates the MDT chambers are known to suffer from a degradation of the spatial resolution due to space-charge fluctuations [6], [7], and of the muon detection efficiency due to the increased tube occupancy [8]. Both effects can be reduced by halving the drift tube diameter.

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The reduction of the tube diameter from 30 to 15 mm has as a consequence a shorter maximum drift time of the electrons, from 700 ns to 200 ns, and lesser dependence of the drift velocity on the drift field, resulting in a more linear space-time relation. Advantages of a faster and more linear gas are: a reduced tube occupancy and less dependency on space charge effects, which enables the drift tube to operate at 7-8 times larger particle flux than the present tubes [9].

OR A LONGER EXPLANATION?

If one neglects electronics effects such as artificial dead time and signal shaping time, the tube occupancy depends on the maximum drift time of the electrons. The space-to-drift-time relationship for the Ar:CO_2 gas mixture used in the MDT chambers is shown in Fig. 1. The maximum drift time is about 700 (200) ns for 30 (15) mm diameter drift tubes, therefore by halving the tube diameter the occupancy is reduced by a factor 3.5. Converted γ particles in the tube wall also contribute to increase the occupancy at high rates. In 15 mm diameter tubes half the conversions take place at the same particle flux. Overall, 15 mm diameter drift tubes have the same occupancy as 30 mm diameter tubes at 7 times higher rates. An additional

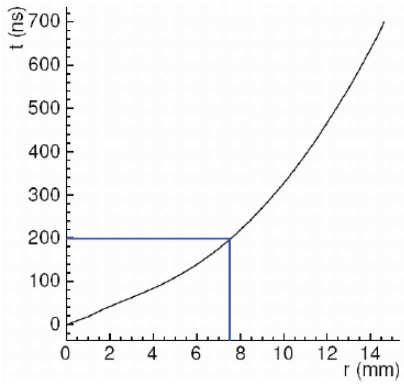

Fig. 1. Space-time relationship for the Ar:CO_2 (93:7) gas mixture at 3 bars currently used in the MDT chambers.

advantage of the reduction of the tube diameter from 30 mm to 15 mm is the increased redundancy in the track measurement since more tubes can be packed into the same volume, which would partly compensate the single-tube efficiency loss. The effect of multiple scattering on the spatial and momentum resolution due to the presence of additional material will be the subject of future investigations - estimation???.

The space-charge distribution generated by the ion clouds drifting toward the tube wall changes the drift electric field, influencing both the drift velocity and the gas gain. By lowering the effective potential seen by the drift electrons, the gas gain decreases at high counting rates. The effective voltage drop grows with the third power of the drift tube radius [10], and is therefore 8 times smaller in 15 mm diameter tubes. The change in the electric field leads to fluctuations of the space-to-drift time relationship, causing a deterioration of the spatial resolution especially in non linear gases, such as the Ar:CO_2 (93:7) mixture used in the ATLAS MDT chambers, since the drift velocity is strongly dependent on the electric field. This effect is not crucial in 15 mm diameter tubes, since the gas response is more linear for drift radii smaller than 7.5 mm. In general, a linear gas is desirable since it entices a lesser dependency on environmental parameters, such as temperature, magnetic field, gas pressure and background radiation. Mixtures other than Ar:CO_2, with fast and linear gas responses, are being investigated. However up to now none has been found that has the same aging properties as Ar:CO_2 (93:7) - add reference??.

III. Design of 15 mm diameter drift tubes

The 15 mm diameter drift tube design follows as much as possible the current ATLAS MDT design. The aluminum tube wall is 400 μm thick, and a 50 μm tungsten-rhenium wire is placed at the center of the tube. The drift tubes are filled with the same gas mixture Ar:CO_2 (93:7) as 30 mm diameter tubes, at 3 bar pressure. The tube operating voltage is set to 2760 V, which corresponds to a gas gain of 25000. The electric field being the same as in the current MDTs for drift radii smaller than 7.5 mm, standard ATLAS MDT electronics can be used for the readout. A summary of the various parameters used for 15 mm and 30 mm diameter drift tubes can be found in Table I.

TABLE I
Comparison of operating parameters for 15 mm and 30 mm diameter drift tubes.

Diameter	15 mm	30 mm
Gas mixture	Ar:CO_2 (93:7)	Ar:CO_2 (93:7)
Gas pressure	3 bar	3 bar
Wire	50 μm W-Re	50 μm W-Re
Tube wall	400 μm Al	400 μm Al
Operating voltage	2760 V	3080 V
Max. drift time	200 ns	700 ns
Gas gain	20000	25000

ADD MORE DETAILS ON ENDPLUG DESIGN AND GAS CONNECTIONS??

IV. Cosmic-ray test in a high radiation environment

A detector prototype with 15 mm diameter drift tubes has been tested in a high radiation environment at the Gamma Irradiation Facility (GIF) at Cern in April 2008. The GIF is equipped with a 590 GBq ^{137}Cs source emitting 662 keV photons. Lead filters of various thickness are available to partially shield the source [11].

The experimental setup at the GIF consisted in two reference chambers used for tracking, 6 15 mm diameter drift tubes of 1 m length placed between the reference chambers, and 2 layers of scintillator counters (6 counters of 1.15 m length per layer) used to trigger on muons from cosmic rays (see Fig. 2). The setup was placed at a distance of about 1.50 m from the source. The counters were shielded from the photon radiation by a 15 cm thick lead wall, who was also partly shielding the lower reference chamber. The reference chambers were made of 2 triple layers of 30 mm diameter drift tubes of 50 cm length (8 drift tubes per layer). The distance between the upper and lower layers of each reference chamber was 31.5 cm, in order to have a good angular resolution for the tracking. To minimize multiple scattering between the test drift tubes and the reference chambers, two spacers made of hollow 30 mm diameter tubes were used to hold the 6 prototype drift tubes in place between the two reference chambers. The length of the 30 mm diameter tubes has been chosen to have the same counting rate per tube as in the 15 mm diameter tubes. This partly compensates the efficiency loss in the reference chambers at high counting rates due to the large occupancy.

The maximum measured counting rate in the small tubes was 1400 $cm^{-2}s^{-1}$, which corresponds to a particle flux 14 times higher than expected in the hottest region of the ATLAS muon spectrometer at LHC design luminosity (without safety factor). By placing appropriate filters in front of the source, measurements were also made at counting rates of 50, 800, and 1100 $cm^{-2}s^{-1}$. The uncertainty on the measurement of the counting rate was of the order of 50 $cm^{-2}s^{-1}$. About 1 million triggers were collected at each counting rate. In the following, a particle flux rate of up to 50 $cm^{-2}s^{-1}$, which

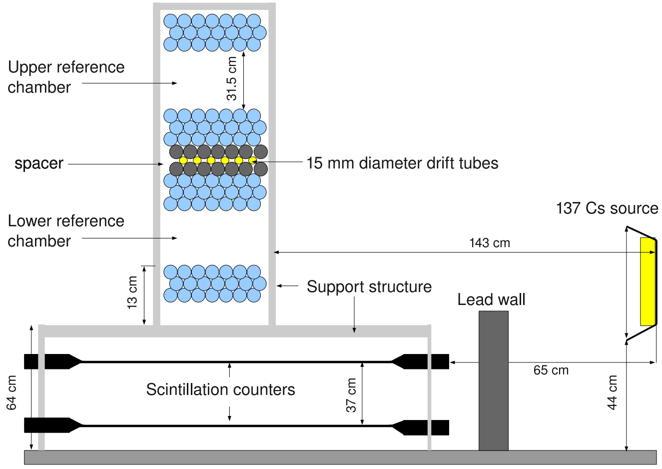

Fig. 2. Schematic drawing of the experimental setup at the GIF.

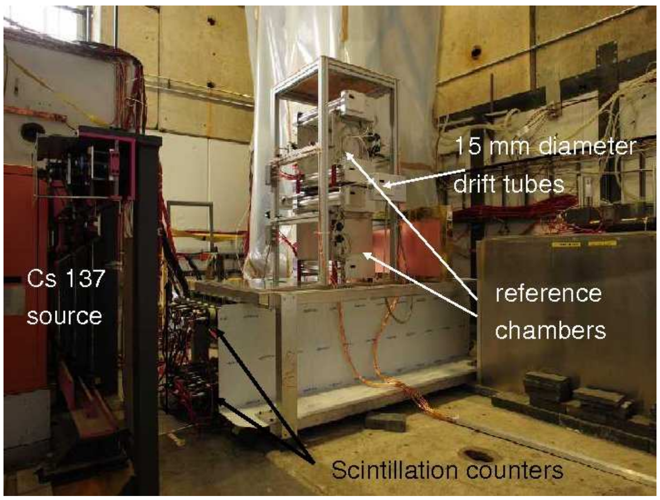

Fig. 3. The experimental setup at the GIF. The lead wall had not been yet built at the time the picture was taken.

corresponds to 7.5 kHz/tube, is referred to as low counting rate.

The readout of both test drift tubes and reference chambers was made with standard ATLAS electronics, which allows for the measurement of the electron drift time and the collected charge from the signal pulse height and length. The deadtime of the electronics for the readout of the 15 mm diameter drift tubes was set to 200 ns, whereas for 30 mm diameter drift tubes the standard ATLAS value of 790 ns was used.

V. Drift properties of 15 mm diameter tubes

Muon tracks from cosmic rays were reconstructed separately in both reference chambers. A vertical track was required in each chamber, and both tracks were required to have similar slope. The position of the muon hit in the 15 mm diameter tube crossed by both tracks was given by the average distance of the two reference tracks (one from each chamber) from the tube wire, $(d_{\mathrm{low}} + d_{\mathrm{up}})/2$.

In Fig. 4 the measured space-time relationship for 15 mm diameter drift tubes is shown. As expected, the maximum drift time is about 200 ns, and the drift velocity has a weak dependence on the drift radius. The hits below the thick band which follows the expected space-time distribution for the mixture Ar:CO_2 (93:7) are due to delta electrons created by the muon in the tube wall.

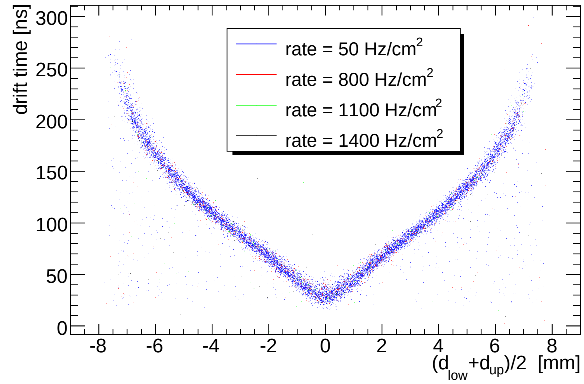

Fig. 4. The space-to-time relationship in 15 mm diameter tubes as a function of the counting rate.

The shown space-time distribution at low rate was used to extract the $r(t)$ relationship, which allows for the determination of the drift radius r from the measured drift time t, as described in [8]. At higher counting rates, however, the number of reconstructed muon tracks decreases by almost a factor 20, due to the degradation of the tracking in the reference chambers and to spurious triggers coming from insufficient shielding of the scintillators. Therefore the $r(t)$ relationship measured at low counting rate was also used to determine the position of muon hits from the measured drift time at high rates. The differences in the $r(t)$ relationships at various rates are smaller than the experimental uncertainties.

VI. Performances of 15 mm diameter drift tubes at high rates

The resolution of the tracking from the reference chambers was measured by fitting with a gaussian distribution the difference of the distances of the two reference tracks from the wire of the 15 mm diameter drift tube crossed by the muon, $(d_{\mathrm{low}} - d_{\mathrm{up}})/2$ (see Fig. 5). At low counting rates, the measured $\sigma_{30\mathrm{mm}}$ was 115 ± 1 μm. At high rates space charge fluctuations cause a significant degradation of the tracking performance, the reference chambers being equipped with 30 mm diameter tube, and the spatial resolution grows linearly up to $\sigma_{30\mathrm{mm}} = 224 \pm 14$ μm at 1400 cm^{-2}s^{-1} (see Table II).

The spatial resolution $\sigma_{15\mathrm{mm}}$ of the 15 mm diameter drift tubes was extracted from the gaussian σ_{res} of the residuals, defined as the difference between the muon hit position determined by the $r(t)$ relationship and the hit position measured by the external tracking reference, $r-(d_{\mathrm{low}}+d_{\mathrm{up}})/2$ (see Fig. 6). $\sigma_{15\mathrm{mm}}$ was calculated by taking the quadratic difference of the σ of the residual distribution and $\sigma_{30\mathrm{mm}}$. At the highest rate of 1400 cm^{-2}s^{-1}, the measurement of the 15 mm diameter resolution is domined by the uncertainty on the measurement of the track position.

TABLE II

TRACKING SPATIAL RESOLUTION, GAUSSIAN σ OF THE RESIDUAL DISTRIBUTION, AND 15 MM DIAMETER DRIFT TUBE SPATIAL RESOLUTION ($\sigma_{30\text{mm}}$, σ_{res}, AND $\sigma_{15\text{mm}}$) AS A FUNCTION OF THE COUNTING RATE.

Counting rate [$\text{cm}^{-2}\text{s}^{-1}$]	$\sigma_{30\text{mm}}$ [μm]	$\sigma_{30\text{mm}}$ [μm]	$\sigma_{30\text{mm}}$ [μm]
50	115 $\pm$ 1	160 $\pm$ 1	114 $\pm$ 2
800	155 $\pm$ 4	195 $\pm$ 6	118 $\pm$ 7
1100	174 $\pm$ 9	221 $\pm$ 13	136 $\pm$ 15
1400	224 $\pm$ 14	246 $\pm$ 17	101 $\pm$ 22

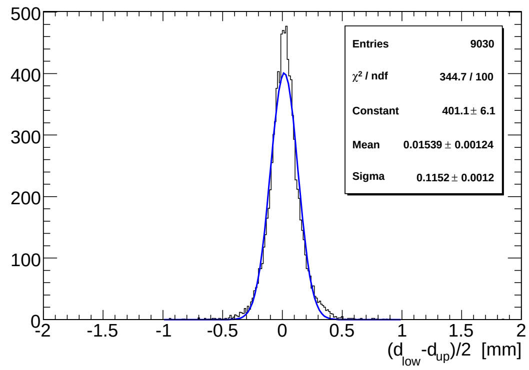

Fig. 5. Difference of the distances of the reference tracks from the wire of the 15 mm diameter drift tube hit by a muon at low counting rate. The tracking resolution was given by the gaussian σ of the ditribution.

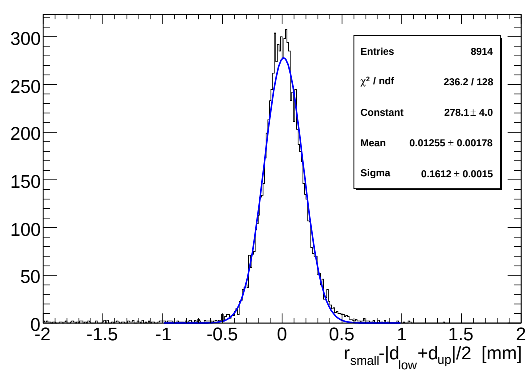

Fig. 6. Residual distribution at low counting rate. The spatial resolution of 15 mm diameter drift tubes was calculated by taking the quadratic difference of the σ_{res} coming from the gaussian fit of the residuals and of the tracking resolution.

The residual distribution is significantly non-gaussian for tracks close to the wire [7]. Moreover space charge fluctuations, who cause variation of the electric field over time and as a consequence a deviation from the expected $r(t)$ relationship, have larger effect at larger radii. The residual distribution is therefore given by the superposition of several gaussian distributions of increasing width. These effects were neglected due to limited available statistics, and the resolution was calculated as described above for all values of r.

VII. DISCUSSION OF THE RESULTS AND COMPARISON WITH PREVIOUS MEASUREMENTS

At low rates, the spatial resolution of 15 mm diameter tubes $\sigma_{15\text{mm}} = 114 \pm 2$ μm, is similar to $\sigma_{30\text{mm}}$. At higher rates however 15 mm diameter drift tubes perform significantly better (see Fig. 7), in agreement with expectations from previous measurements. The predictions were obtained by averaging the spatial resolution of 30 mm diameter drift tubes measured in a 2004 testbeam for drift radii smaller than 7.5 mm [12].

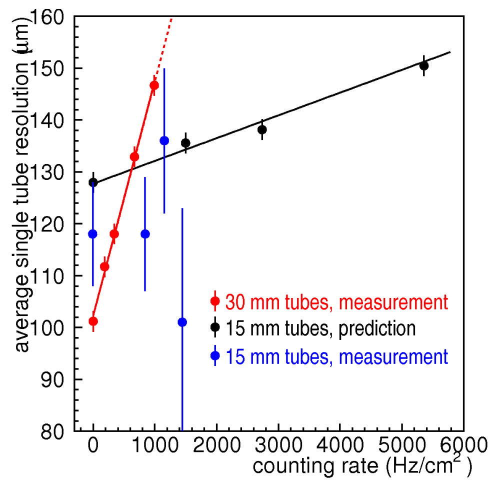

Fig. 7. Spatial resolution of 15 mm and 30 mm diameter drift tubes as a function of the counting rate. The 30 mm diameter drift tube measurement were made in a 2004 testbeam at the GIF [12].

Non-gaussian tails in the residuals distribution may arise due to delta rays and background hits. The 3σ efficiency, defined as the probability that the reconstructed muon radius is within 3σ from the value predicted by the external reference tracking, was used to characterize the importance of such tails. In Fig. 8 the measured 3σ efficiencies for 15 mm and 30 mm diameter drift tubes are shown as a function of the counting rate.

The 5% inefficiency at low counting rate for both 15 and 30 mm diameter drift tubes is due to the creation of delta electrons in the tube wall. At higher rate the degradation of the performances is due to background hits. Measurements for 30 mm diameter drift tubes were made in a testbeam in 2004 [12], and correspond to data taken with the standard ATLAS deadtime of the electronics, 790 ns, and with a shorter deadtime, 200 ns. If a muon arrives in the dead-time window after a background hit, the muon hit is not detected. Hence reducing the electronics deadtime has as a consequence an increased tube efficiency. To improve the efficiency in data taken with 200 ns deadtime and multiple hits in a single event, muon hits were recovered by using the second hit if the first one had a radius falling outside the required 3σ window. The 3σ efficiency for 15 mm diameter drift tubes is similar to that of 30 mm diameter tubes with 200 ns deadtime and second hit recovery.

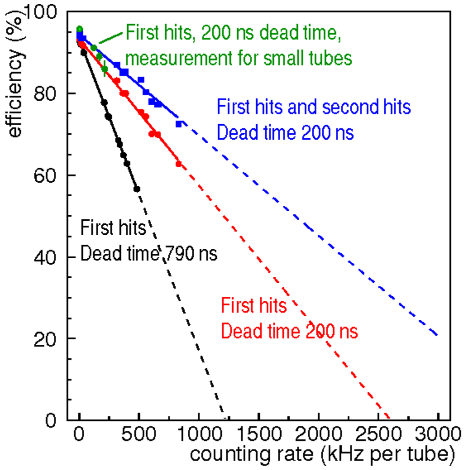

Fig. 8. 3σ single tube efficiency for 15 mm and 30 mm diameter drift tubes as a function of the counting rate. The green dots are measurements from the GIF tests described in this letter, whereas the remaining curves were measured in 2004 tests of 30 mm diameter tubes at the GIF [12].

VIII. Conclusion

The ATLAS MDT chambers are designed to withstand particle fluxes up to 500 $cm^{-2}s^{-1}$. However counting rates up to 5 kHz/cm^{-2} are to be expected at a luminosity of $10^{35}cm^2s^{-1}$ at the Super-LHC, the luminosity upgrade foreseen for the LHC. We investigated the performances of drift tubes with smaller diameter (15 mm against 30 mm of the current MDT design). A prototype detector equipped with such small tubes was tested in a high radiation environment, with counting rates up to 1.4 kHz/cm^{-2}. A spatial resolution of 114 ± 2 μm was measured at low counting rate, and the tube performances were stable with increasing background rates. At low counting rate the 3σ single tube efficiency was 95% (inefficiency due to delta rays), and the degradation at higher counting rates was found in agreement with expectations. The smaller diameter drift tubes can therefore be considered a promising solution for the replacement of MDT chambers in the hottest region of the ATLAS muon spectrometer at the Super-LHC luminosity. However more conclusive tests are still needed to demostrate that a chamber equipped with small tubes could meet the design requirements of the ATLAS MDT chambers, i.e. ensure a chamber spatial resolution of at least 35 μm. In particular, multiple scattering effects within a chamber due to the increased amount of material (in case more drift tubes than in the present design are needed) need to be better understood. We plan to build a chamber prototype equipped with 15 mm diameter tubes and test it in the GIF during 2009.

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