Operation of the ATLAS Muon Drift-Tube Chambers at High Background Rates and in Magnetic Fields

S. Horvat†, D. Khartchenko*, O. Kortner, S. Kotov*, H. Kroha, S. Mohrdieck-Möck, K. Nikolaev*, R. Richter, W. Stiller, Ch. Valderanis,
Max-Planck-Institut für Physik, Föhringer Ring 6, D-80805 Munich, Germany,
J. Dubbert, F. Rauscher, A. Staude,
Ludwig-Maximilians-Universität München, Am Coulombwall 1, D-85748 Garching, Germany

***Abstract*— In the ATLAS muon spectrometer, large drift-tube chambers are used for precision tracking. The chambers will be operated at a high neutron and γ background resulting in count rates of up to 500 $\mathrm{Hz\,cm^{-2}}$ corresponding to 300 kHz per tube. The spatial resolution of the drift tubes is degraded from 82 μm without background to 108 μm at 500 $\mathrm{Hz\,cm^{-2}}$ background count rate. Due to afterpulsing in the $\mathrm{Ar/CO_2}$ gas mixture used in the drift tubes, ionizing radiation causes more than one hit in a tube within the maximum drift time of about 800 ns which is expected for magnetic field strengths around 1.2 T. In order to limit the count rate, the drift tubes are read out with an artificial dead time of 790 ns which causes an efficiency loss of 23% at a rate of 300 kHz per tube. The space-to-drift-time relationship of the tubes varies with background rate, temperature, and magnetic field strength. The mean magnetic field strenght in a muon chamber is 0.4 T on the average, but may vary by up to 0.4 T within a chamber. The space-to-drift-time relationship must therefore be determined in short time intervals with an accuracy better than 20 μm using muon tracks and applying corrections for measured magnetic field variations.**

***Index Terms*— ATLAS detector, muon spectrometer, drift tubes, autocalibration.**

I. Introduction

IN the muon spectrometer of the ATLAS detector [1] at the Large Hadron Collider (LHC), three layers of large drift tube chambers, the Monitored Drift Tube (MDT) chambers, are used for precision tracking in the toroidal field of superconducting air core magnets. The MDT chambers consist of two triple or quadruple layers (multilayers) of aluminium drift tubes with 30 mm diameter and 0.4 mm wall thickness mounted on either side of an aluminium space frame. In order to achieve a momentum resolution <10% for muon momenta of up to 1 TeV, the chambers have to provide a spatial resolution of 45 μm. With a 20 μm positioning accuracy of the sense wires within a chamber, the spatial resolution of a drift tube has to be better than 110 μm. The drift tubes are filled with an Ar:CO2 (93:7) gas mixture at 3 bar and are operated at a gas gain of $2 \cdot 10^4$.

The ATLAS muon chambers will experience unprecedentedly high neutron and photon background count rates, which have a significant impact on their performance [2] [3]. At the LHC design luminosity of 10^{34} $\mathrm{cm^{-2}\,s^{-1}}$, count rates of up to 500 $\mathrm{Hz\,cm^{-2}}$ (including a safety factor 5) are expected. This corresponds to a count rate of 300 kHz per tube for the largest tubes in the region of highest background. The count rates are highest in the forward regions of the muon spectrometer. The maximum is reached in the layer closest to the interaction point. The neutron and γ background is caused by the hadrons in the proton-proton collisions by interactions with the calorimeters, shielding material, and accelerator elements. As the muon chambers are operated in air instead of magnetized iron absorbers, thermalized neutrons from the hadronic interactions and photons from (n,γ) interactions penetrate the muon spectrometer and hit the muon chambers. The neutron and γ background is not correlated with the initial proton-proton collisions due to frequent rescatterings of the neutrons and photons. [1]

In order to test the performance of the MDT chambers at background rates as in ATLAS, one of the largest precision muon chambers for the ATLAS detector equipped with final electronics was operated in the Gamma Irradation Facility (GIF) at CERN [4] in summer 2003 and 2004. This facility provides a 100 GeV muon beam and a 664 GBq ^{137}Cs source emitting 662 keV photons used to simulate the ATLAS background radiation.

The space-to-drift-time relationship $r(t)$ of the tubes varies with the magnetic field strength, the background rate, and the temperature. While the magnetic field is constant in time, the temperature and the background rate vary in time. The background rate is expected to vary by up to 50% within 10 hours which implies changes in $r(t)$ greater than 20 μm in region of high background. Therefore, the space-to-drift-time relationship must be determined in short time intervals of about 2 hours with an accuracy better than 20 μm by using muon tracks and applying magnetic field corrections. Efficient autocalibration algorithms and the dependence of the $r(t)$ relationship were also studied with data acquired under higher γ irradition rates at the GIF.

†On leave of absence from Institut Ruđer Bošković, 10 001 Zagreb, Croatia.
*Permanent address: JINR, 141980 Dubna, Russia

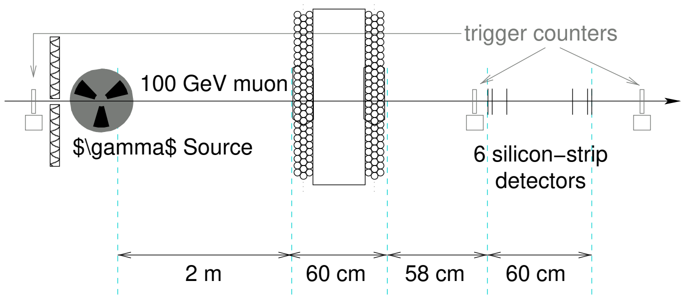

Fig. 1. Top view of the experimental set-up at the Gamma Irradiation Facility with the 665 GBq ^{137}Cs γ source, the MDT chamber, and a silicon tracking detector.

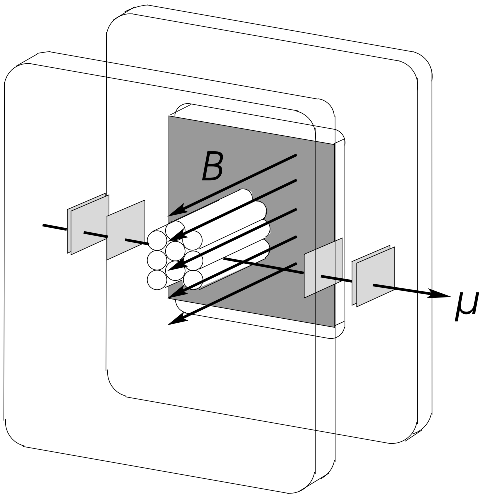

Fig. 2. A small MDT chamber in the middle of the silicon tracking detector within the homogenous field of a dipole magnet.

II. Test-Beam Set-up

In the Gamma Iradiation Facility, a chamber with 432 tubes of 3.8 m length in two triple layers separated by 317 mm was installed at 2 m distance from the radioactive source as sketched in Figure 1. The chamber could be rotated by up to 38^o around the vertical axis parallel to the tubes in steps of 2.5^o. In addition a chamber with 3×3 tubes in the middle of the telescope was operated in a 0-0.9 T dipole field parallel to the anode wires of the tubes (see Figure 2).

A telescope consisting of two times three silicon strip detectors 60 cm apart was placed at 58 cm distance behind the chamber. Each of the four inner strip detectors measured the lateral position of incident muons with an accuracy of 10 μm. The two outermost detectors measured the vertical positions of the muon tracks with the same accuracy. The active areas of the silicon detectors were 5×5 cm^2.

The beam telescope was enclosed by two fast scintillation counters of the same active area. The coincidence of these two counters with a 10×10 cm^2 scintillation counter placed in the beam upstream where it was protected from the radiation of the γ source provided the trigger signal for the data acquisition. The time jitter of the trigger time was negligible with respect to the time resolution of the drift tubes (3 ns). The positions of the muon trajectories are measured with high accuracy by the silicon telescope independently of the drift-tube chamber.

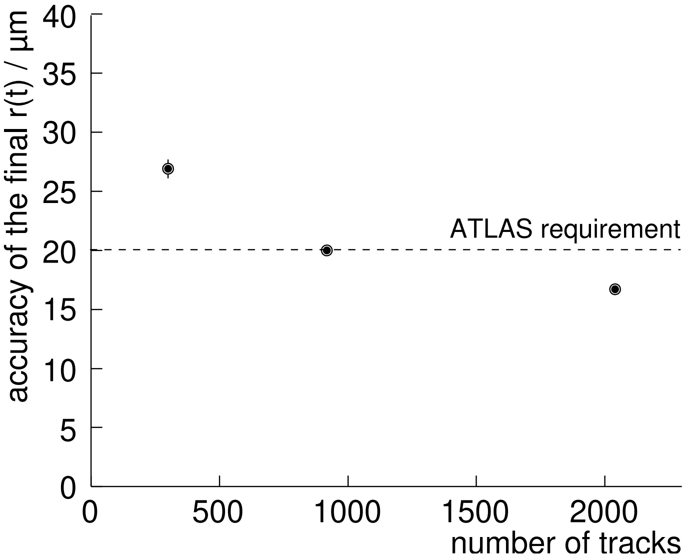

Fig. 3. Dependence of the autocalibration accuracy on the number of tracks used in the calibration procedure.

Each drift tube is read out by a chain of a preamplifier, shaper, and discriminator [6] capacitively coupled to the sense wire. A TDC measures the arrival times of the signals for each tubes in a group of 24. Bipolar shaping is used with a peaking time of 15 ns [6]. The discriminator threshold is adjustable around a nominal value corresponding to the amplitude of the signal created by 16 primary electrons which is 4.8 times the standard deviation of the thermal noise at the input of each discriminator. The pulse heights are measured by an ADC in each of the 24 channels. Bipolar shaping was chosen in order to avoid baseline shifts of the analog signals caused by multiple hits in presence of high radiation background in the ATLAS muon spectrometer. A consequence of bipolar shaping are multiple crossings of the discriminator threshold. These secondary threshold crossing can be masked by an artificial dead time of 790 ns after each detected hit [2]. The dead time of the electronics is adjustable between 200 ns to 790 ns. As the mean multiplicity of γ hits is 1.83 ± 0.07 at 200 ns dead time and the bandwith of the further read-out chain is limited to a hit rate of 500 kHz per tube, the electronics is operated with a fixed artificial dead-time of 790 ns where the γ hit multiplicity is 1 so that the data rate is kept below the bandwidth limit.

III. Autocalibration with Muon Tracks

The space-to-drift-time relationship $r(t)$ of the drift tubes changes with the operating conditions, mainly the magnetic field strength, the temperature, and the background rate. The temperature and the radiation background are expected to be the same in an area of about 1 m^2 within a multilayer of a chamber. Using the temperature and the count rate measured in the 1 m^2 regions, it is possible to calculate the $r(t)$ relationship

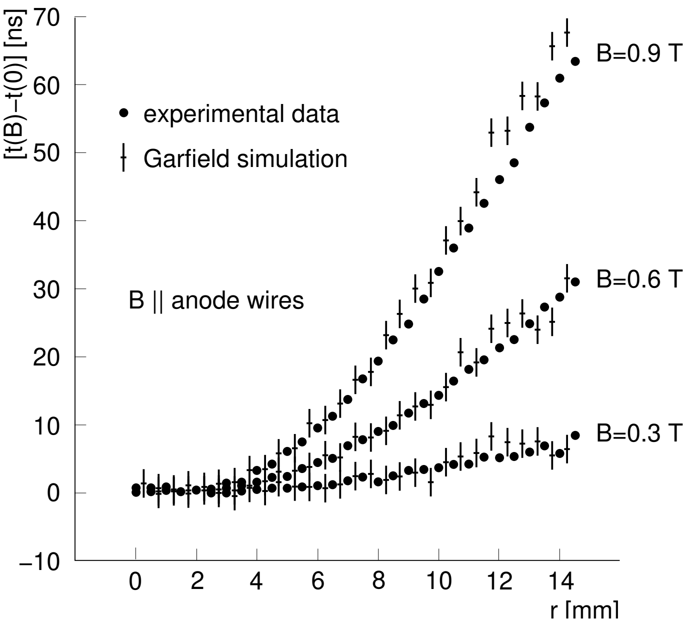

Fig. 4. Change in the drift time t caused by the magnetic field B parallel to the sense wires as a function of the muon impact radius r. The dots show the results of test-beam measurements and the crosses the prediction of the simulation with the Garfield programme [7].

with 200 μm accuracy with the Garfield simulation programme [7]. Muon tracks are used to refine the initial $r(t)$ estimate to the required accuracy of 20 μm.

Muon tracks can be considered straight lines inside each multilayer. The track reconstruction starts with the initial $r(t)$ relationship. The measure of the quality of the $r(t)$ relationship are the residuals $\Delta_k := r(t_k) - d_k$ where d_k denotes the distance of the reconstructed track from the k-th sense wire along the track and $r(t_k)$ the drift radius of the k-th hit. Using the residuals from tracks with different incidence angles and making use of the functional dependence of the residuals on $r(t)$, an improved estimate of $r(t)$ can be extracted from the residuals [8]. Tracks with different incidence angles and the functional dependence of the residuals on $r(t)$ are needed to resolve ambiguities in the minimization of the residuals $\Delta_k = 0$. The refinement of the $r(t)$ relationship is iterated until the quantity $\sum_k [\Delta_k/\sigma(r(t_k))]^2$ ($\sigma(r(t_k))$ denotes the spatial resolution at $r(t_k)$) reaches a minimum value. Studies based on Monte-Carlo data show that this autocalibration prodecure converges to the correct $r(t)$ relationship with an accuracy of 20 μm using only 1000 tracks (see Figure 3) which can be detected inside a 1 m^2 calibration region within typically 1 hour at a luminosity of 10^{34} cm^{-2}s^{-1}. The results of the Monte-Carlo study have been confirmed by applying the autocalibration procedure to test-beam data.

IV. B-Field Corrections to $r(t)$

The component of the toroidal magnetic field parallel to the anode wires of the drift tubes varies by up to 0.4 T along the tubes, in particular at the ends of the magnet coils

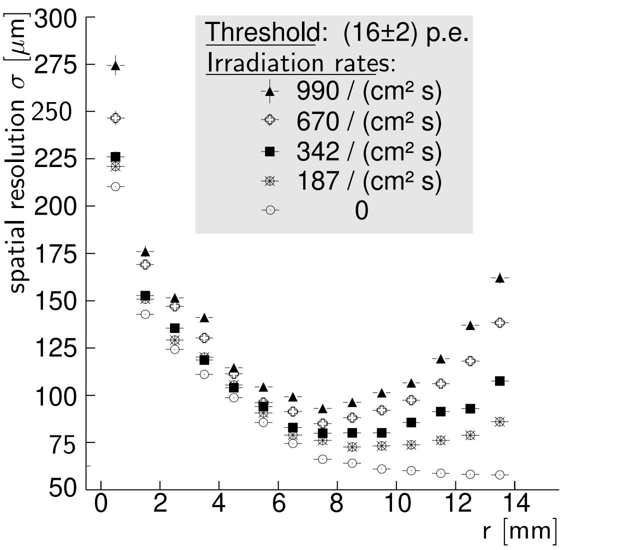

Fig. 5. Spatial resolution of a drift tube as a function of the drift distance at different background rates. The discriminator threshold used corresponds to the (16±2)th primary electron.

[1]. As the Lorentz force bends the drift paths of the electrons, the $r(t)$ relationship is altered by the magnetic field parallel to wire of the tubes. In order to be able to perform the autocalibration procedure, the magnetic field dependence of the $r(t)$ relationship has to be taken into account. Figure 4 shows the effect of the magnetic field strength on the drift time as a function of the muon impact radius. Measurement and simulation agree within better than 3 ns. An error of 3 ns on the prediction of the maximum drift time corresponds to an error in the drift distance of about 60 μm at large radii. In order to reduce it to 10 μm, the prediction of the maximum drift time in the magnetic field must be accurate to 0.5 ns. The measured magnetic-field depence of $r(t)$ will allows us to improve the simulation to reach the required accuracy of 0.5 ns.

V. Impact of the Background Radiation on the Spatial Resolution

The neutron and γ background in the ATLAS cavern will lead to count rates of up to 500 Hz cm^{-2} in the MDT chambers. The space charge created by the ionizing radiation in the drift tubes lowers the electric field near the anode wires. As a consequence, the gas gain is decreased. The measured gain drops by 9% at the maximum expected background rate of 500 Hz cm^{-2}, which leads to a reduction of the spatial resolution of the drift tubes by 30 μm near the anode wires.

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 the Ar:CO_2 gas, the fluctuations of the electric field causes fluctuations of the $r(t)$ relationship. The effect increases with the drift path. Figure 5 shows the degradation of the spatial resolution of the drift tubes as a function of the drift distance with increasing count rates.

Figure 6 shows the quadratic average of the spatial resolution of the drift tubes as a function of the background rate. It

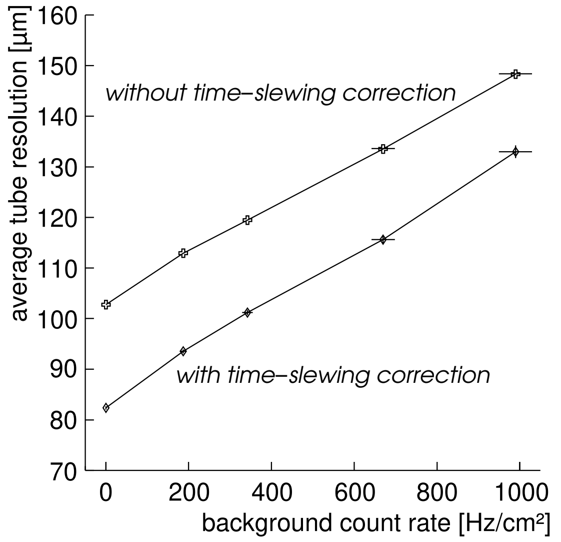

Fig. 6. Spatial resolution of the drift tubes as a function of the background count rate with and without time-slewing corrections.

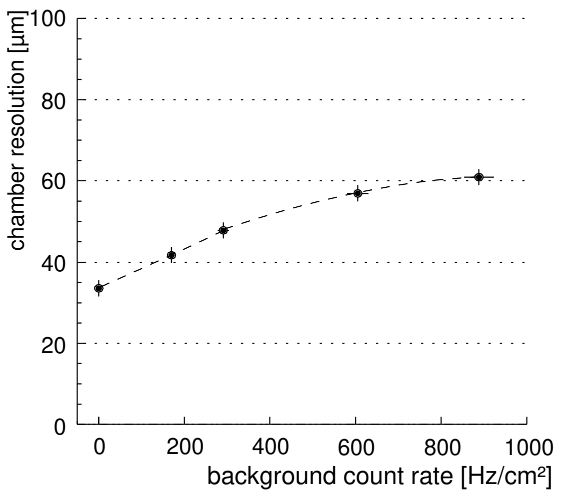

Fig. 7. Spatial resolution of a six-layer chamber as a function of the background count rate.

does not meet the requirement of a resolution better than 110 μm. Using the pulse-height measurement of the front-end electronics to apply time-slewing corrections [2], a drift-tube resolution of 82 μm is obtained without background radiation corresponding to a chamber resolution of 34 μm (see Figure 7) in a six-layer chamber; the tube resolution is still 108 μm at 500 Hz cm^{-2} count rate, which corresponds to 45 μm chamber resolution. The time-slewing (i.e. the walk of the discriminator-threshold crossing time of the signals with their amplitudes) is a contribution to the time, hence the spatial resolution, which has to be added quadratically to other sources of the limited time (spatial) resolution. Figure 6 shows that the time slewing corrections are the more effective the higher the γ background rate. The reason for this behaviour is the fact that the time slewing is inversely proportional to the pulse height. Due to the gain drop at large γ background, the time slewing is therefore larger at higher γ background rates.

VI. Impact of the Background Radiation on the Muon Detection Efficiency

THE neutron and γ background also leads to a reduced muon detection efficiency. After a detected hit in a tube, the read-out electronics cannot detect another hit within the fixed dead time of 790 ns after the first hit. Hence a muon hit is not detected when it falls into the dead-time window after a preceding background hit. In the test-beam data, background hits can be distinguished from muon hits by comparing their drift radii $r(t_k)$ with the distances d_k of the tracks reconstructed with the silicon detectors from the anode wires. If

$$|r(t_k) - d_k| < 3\sigma(d_k)$$

where $\sigma(d_k)$ denotes the spatial resolution of the tube k at the radius d_k, the hit is accepted as a muon hit and otherwise considered a background hit.

Figure 8 shows the measured single-tube efficiency as a function of the background rate. It decreases with increasing background as expected for a dead time of 790 ns. Even without background, it is only 94% because δ electrons knocked out of the tube walls by the incoming muons cause hits at radii closer to the anode wire than the muon hits. The drift-tube efficiency decreases to 89% at the nominal maximum count rate of 60 kHz per tube. If the background rate is five times larger, the efficiency is significantly reduced to 72%. If tracks of perpendicular incidence on the 6-layer chamber in the test beam are reconstructed, a higher efficiency is achieved because of the redundancy of the track point measurements (see Figure 9). Track-reconstruction efficiencies between 90% and 95% are observed at background rates similar to those in 6-layer chambers in the muon spectrometer. At five times higher rates efficiencies between 80% and 85% are reached. The track reconstruction efficiency is the ratio $\frac{n_{MDT}}{n_{ext}}$, where n_{ext} denotes the number of tracks reconstructed by the external silicon tracker and n_{MDT} the number of track reconstructed in the muon chamber which agree within 3 times the chamber resolution with the track as reconstructed by the external silicon tracker.

At background rates of 60 kHz per tube, for instance for a luminosity upgrade of the LHC, the tracking efficiency will be reduced to about 65%.

In order to explore the efficiency limit at very high background rates with the present front-end electronics, data were acquired with the minimum artificial dead-time setting of the read-out electronics of 200 ns. In this case a drift-tube can have more than one hit per trigger, because the signal crosses the discriminator threshold more than once. Muons and photons cause about 1.5 hits per trigger on the average. Therefore, the count rates is higher than at the large dead time of 790 ns at the same photon flux.

The data were analysed in two ways:

1) Only the hit first in time was considered. As the dead time is much shorter than the maximum drift time of

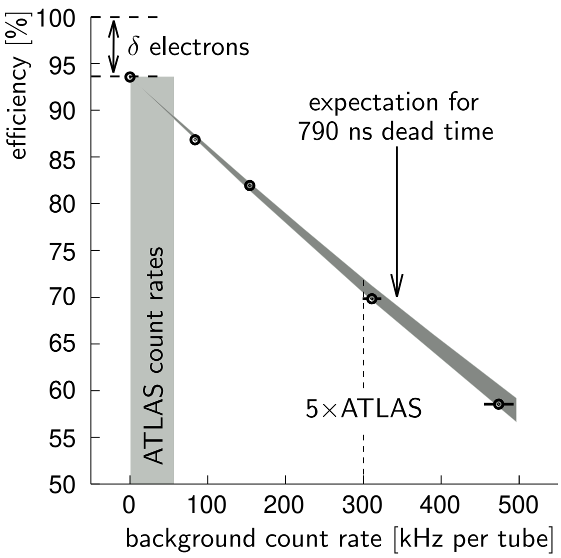

Fig. 8. Single-tube efficiency as a function of the background count rate at a dead-time setting of 790 ns.

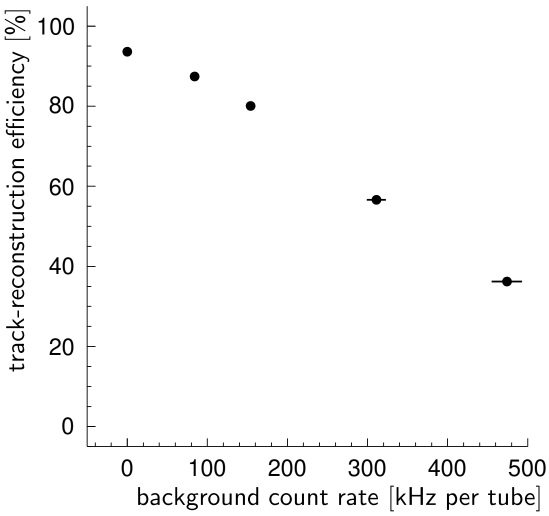

Fig. 9. Track reconstruction efficiency achieved in a six-layer chamber at perpendicular track incidence with 790 ns dead time.

about 700 ns, the single-tube efficiency is increased (see Figure 10). The efficiency increase is 2.5% at the maximum nominal background of 60 kHz per tube. At a rate of ten times the ATLAS maximum, the efficiency gain is 10%.

2) Whenever the first hit gave a wrong radius and another hit was detected in the same tube in the same event, the second hit was used. This enabled us to recover muon hits which are more than 200 ns after a background hit. As a consequence, the efficiency is further improved. It is greater than 80% for rates of up to 10 times the maximum rate expected in ATLAS.

Whether the tracking efficiency also rises, when the single-tube efficiency rises, depends on the ability of the pattern and track-finding algorithm to select the correct hits out of the bulk of

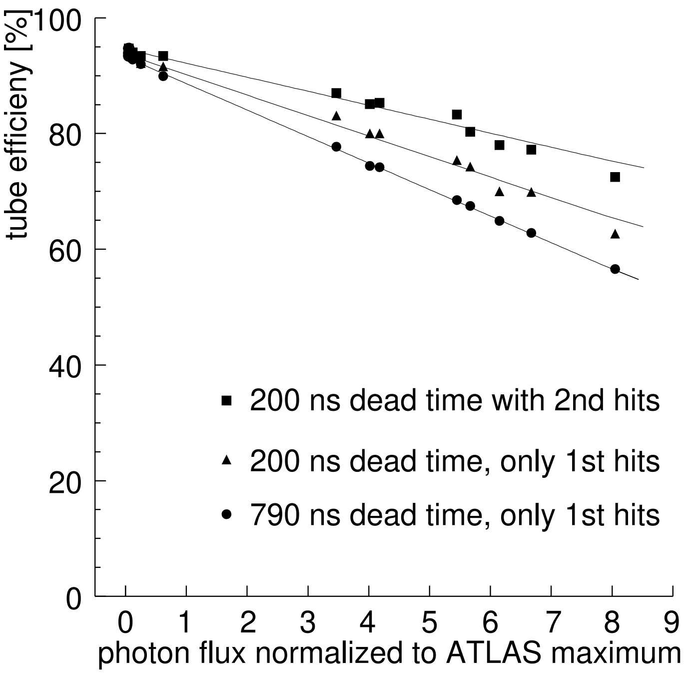

Fig. 10. Muon detection efficiency of a drift tube as a function of the photon flux for different artificial dead times. The photon flux of 1 time the ATLAS maximum corresponds to a background count rate of 60 kHz per tube at 790 ns dead time. The lines represent linear fits to the measured efficiencies.

first and second hits in a chamber. Studies [10] indicate that the tracking efficiency in the ATLAS muon spectrometer can also be improved in this way in spite of the higher occupancy. At the present design of the full read-out chain, however, it is not possible to lower the dead time to 200 ns for the operation in ATLAS because of the limited bandwidth of the read-out chain.

VII. Conclusions

The precision drift tube chamber for the ATLAS muon spectrometer will be able to measure track points with an accuracy better than 45 μm up to the highest background rates of 500 $\mathrm{Hz\,cm^{-2}}$. The high spatial resolution is achieved with a 20 μm positioning accuracy of the sense wires, a single-tube resolution of better than 108 μm up to 500 $\mathrm{Hz\,cm^{-2}}$ and by determining the space-to-drift-time relationship $r(t)$ with an accuracy better than 20 μm. An autocalibration procedure using muon tracks within a multilayer of a chamber has been developed which allows for a calibration of the $r(t)$ relationship with 20 μm accuracy in 1 $\mathrm{m^2}$ regions of the chambers per hour during the operation at the LHC with 10^{34} $\mathrm{cm^{-2}\,s^{-1}}$ luminosity. In chambers close to the ends of the magnet coils of the muon spectrometer, the magnetic field varies by up to 0.4 T within an autocalibration region. In this case magnetic field corrections to the $r(t)$ relationship must be applied, which are based on Garfield calculations and the test-beam measurements described in Section IV.

The muon drift-tube chambers will be exposed to an unprecedently high neutron and γ background in the ATLAS cavern. In order to keep the count rates of the chambers within the bandwidth of the read-out chain, the tubes are read out with an artificial dead-time of 790 ns. The track reconstruction efficiency in an individual chamber was measured to be above 90% for background count rates up to 60 kHz per tube (100 $\mathrm{Hz\,cm^{-2}}$) and above 80% up to five times higher rates.

ACKNOWLEDGMENT

The authors would like to thank M. Clayton, L. Gatignon, and P. Pierre of CERN for providing us with the dipole magnet for our studies, A. di Girolamo and M. Kollefrath for lending us equipment and T. Christiansen and J. Gregory for helping us in the development of the data acquisition software.

REFERENCES

[1] The ATLAS Muon Collaboration, "ATLAS Muon Spectrometer – Technical Design Report", CERN/LHCC 97-22, Geneva, 1997.

[2] M. Aleksa et al. (1999, July), "Rate Effects in High-Resolution Drift Chambers", *Nucl.Instrum.Meth.A446* (2000).

[3] M. Deile et al., "Performance of the ATLAS Precision Muon Chambers under LHC Operating Conditions" in *Proc. Of the 9th Pisa Meeting on Advanced Detectors*, 2003, pp. 65-68, *Nucl.Instrum.Meth.A518* (2004).

[4] S. Agosteo et al. (March 2000), "A facility for the test of large-area muon chambers at high rates", *Nucl.Instrum.Meth.A452* (2000).

[5] W. Riegler et al. (July 1999), "Front-End Electronics for Drift Tubes in a High-Rate Environment", *Nucl.Instrum.Meth.A446* (2000).

[6] C. Posch et al., "CMOS front-end for the MDT sub-detector in the ATLAS Muon Spectrometer – development and performance", contribution to the 7th Workshop on Electronics for LHC Experiments LEB 2001 , Stockholm, Sweden , 10 - 14 Sep 2001 - pages 199-203.

[7] R. Veenhof, "GARFIELD: Simulation of gaseous detectors, Version 8", CERN 2002.

[8] M. Deile et al., "Autocalibration: The Influence of the Track Incidence Angles and a New Method", ATLAS internal note, Geneva 2000.

[9] M. Deile, "Optimization and Calibration of the Drift-Tube Chambers for the ATLAS Muon Spectrometer", doctoral thesis, Ludwig-Maximilians-Universität München, 2000.

[10] J.F. Laporte et al., "On the Number of Layers per Multilayer in MDT Chambers PartI", ATLAS internal note, Geneva, 1996.