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

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***Abstract*— In the ATLAS muon spectrometer, large drift-tube chambers are used for precision tracking. These chambers will be operated at a high neutron and $\gamma$ background resulting in count rates of up to 500 counts $s^{-1}\,cm^{-2}$ corresponding to 300 kHz per tube. The spatial resolution of the drift tubes is degraded from 82 $\mu$m without background to 108 $\mu$m at 500 Hz $cm^{-2}$ background count rate. In order to limit the background 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 relationships of the tubes vary with the background rate, the temperature, and the magnetic field strength. They must be recalibrated in short time intervals with an accuracy better than 20 $\mu$m which is guaranteed by an autocalibration procedure using muon tracks and by applying measured magnetic field corrections to the relationship.**

***Index Terms*— ATLAS, muon spectrometer, high rates, magnetic field, autocalibration.**

## I. Introduction

In the muon spectrometer of the ATLAS detector at the Large Hadron Collider (LHC), 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 of aluminium drift tubes with 30 mm diameter and 0.4 mm wall thickness mounted on either side of an aluminum space frame containing optical deformation monitoring systems. In order to achieve a momentum resolution of better than 10% up to muon momenta of 1 TeV, the chambers have to provide a spatial resolution of 45 $\mu$m. With a positioning accuracy of 20 $\mu$m of the sense wires within a chamber, the spatial resolution of a drift tube has to be better than 110 $\mu$m using an Ar:CO2 (93:7) gas mixture at 3 bar and a gas gain of $2 \cdot 10^4$. [1]

In the ATLAS experiment, the 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 $10^{34}$ $cm^{-2}\,s^{-1}$, count rates of up to 500 Hz $cm^{-2}$ (including a safety factor 5) have to be expected in the inner forward layers of the muon spectrometer. The neutron and $\gamma$ background is created in interactions of primary hadronic collision products with the forward calorimeter, shielding material, and other accelator elements. Low-energy neutrons are produced during the absorption of hadrons. They excite nuclei of the absorbing material which deexcite by emitting $\gamma$ particles. The neutrons and $\gamma$ particles lose any correlation with the initial proton collisions of the LHC by frequent rescattering. Some of the neutrons and $\gamma$ particles escape the material and enter the muon spectrometer where they form a permanent background. [1]

In order to test the performance of the MDT chambers under an ATLAS-like $\gamma$ background, one of the largest precision muon chambers of the ATLAS detector was operated in the Gamma Irradation Facility (GIF) at CERN in 2003. This facility is well-suited for the investigation as it provides a 100 GeV muon beam and a radioactive 664 GBq $^{137}$Cs source emitting 662 keV $\gamma$s for the simulation of the ATLAS $\gamma$ background [4]. The chamber was equipped with the final read-out electronics.

The space-to-drift-time relationships of the tubes vary with the background rate, but also with the temperature and the magnetic field strength. They must therefore be recalibrated in short time intervals with an accuracy better than 20 $\mu$m which has to be guaranteed by an autocalibration procedure using muon tracks and by applying magnetic field corrections to the relationship. The development of a performant autocalibration algorithm and the measurement of the change of the space-to-drift-time relationship $r(t)$ with the magnetic field were the major issues of another test in the GIF in summer 2004.

## II. Test-Beam Set-up

In the GIF, a chamber with 432 tubes of 3.80 m length in two triple layers separated by a 317 mm thick spacer 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 in steps of $2.5^o$. In another test 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.

A telescope consisting of four silicon strip detectors was placed 50 cm in front of the chamber. Each strip detector

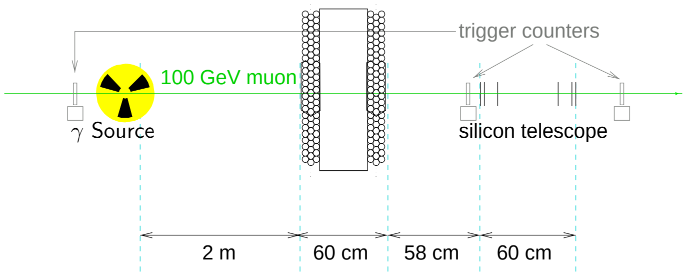


Fig. 1. The experimental set-up at the GIF in 2003 with the 665 GBq $^{137}$Cs $\gamma$ source, the MDT chamber, and a silicon tracking detector. In 2004 a chamber with 3×3 tubes in the middle of the silicon detector was operated in a 0-0.9 T dipole field parallel to the anode wires of the tubes.

measured the lateral positions of the incident muons with an accuracy of 10 $\mu$m. The two outermost detectors measured the vertical positions of the muon hits with the same accuracy, in addition. The active areas of the silicon detectors had a size of 5×5 cm$^2$.

The beam telescope was enclosed by two fast scintillation counters of the same active area. A coincidence of these two counters with a 10×10 cm$^2$ scintillation counter protected from the photon source upstream in the beam provided the trigger signal for the data acquisition. Because of the high time resolution of less than 200 ps, the time jitter of the trigger time was negligible with respect to the time resolution of the drift tubes, which is about 3 ns. The merit of the silicon telescope is that it allows for the accurate reconstruction of the muon trajectories independently of the hits registered by the drift-tube chamber.

The read-out of the ATLAS muon chambers is performed in groups of 24 tubes in the following way: bundles of 24 tubes (3 times 8 in a triple layer) are connected to so-called ”*hedgehog cards*”. A hedgehog card capacitively decouples the signals from the tubes connected and leads them to the so-called ”*mezzanine cards*” mounted on top of the hedgehog card. The mezzanine card contains the amplifiers, the shapers, the discriminators, and the time-to-digital converters for the signals of each of the 24 tubes connected to the hedgehog card. Earlier beam tests in the GIF [2] and simulation studies [5] have lead to the decision to use bipolar shaping with a peaking time of 15 ns. The front-electronics also permits the measurement of the pulse heights in all 24 channels [6]. The dead time of the electronics is adjustable between 200 ns to 790 ns. As the mean multiplicity of $\gamma$ hits is 1.5 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 790 ns dead-time, in order to keep the data rate below the bandwidth limit.

## III. Autocalibration using Muon Tracks

The space-to-drift-time relationship $r(t)$ of the tubes inside a chamber changes with the operating conditions, mainly the temperature and the background rate. The operating conditions are expected to be the same in an area of about 1 m$^2$ of a multilayer of a chamber. Using the temperature and the background rate measured in this area of 1 m$^2$, it is possible to calculate an $r-t$ relationship of 200 $\mu$m accuracy with the Garfield simulation programme [7]. Muon tracks are used to refine the initial $r(t)$ estimate to the required accuracy of 20 $\mu$m.

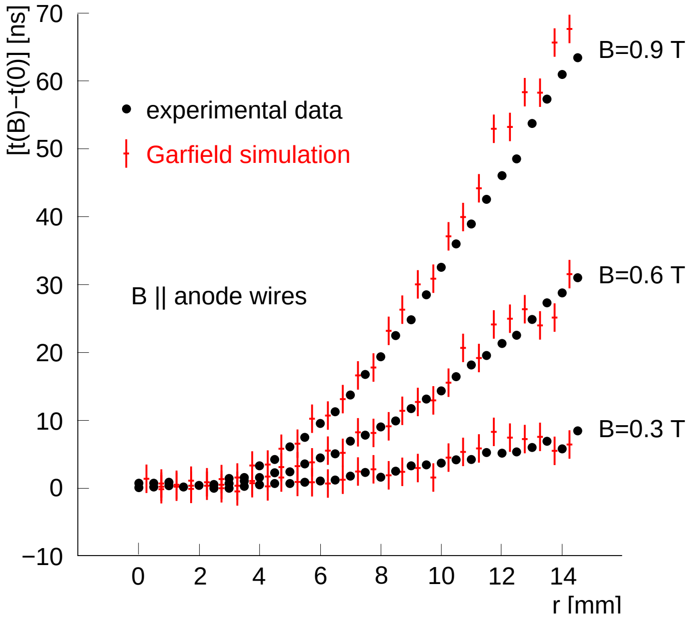


Fig. 2. Change of the $t(r)$ relationship caused by different magnetic fields as a function of the muon impact radius $r$. The round points show the results of test-beam measurements, the crosses the prediction by the Garfield simulation programme.

The muon tracks can be considered straight inside a multilayer. They are reconstructed with the initial $r-t$ relationship. The quality of this $r-t$ relationship is determined by calculating the residuals $\Delta_k := r(t_k) - d_k$ where $d_k$ denotes the track distance from the $k$-th anode wire hit and $r(t_k)$ the drift radius of the $k$-th hit. By making use of the residuals from tracks with different incidence angles and the functional dependence of the residuals on $r(t)$, a better estimate of $r(t)$ can be extracted from the residuals [8]. The new estimate can be improved by repeating this procedure. The iterative refinement of $r(t)$ is terminated when the quantity $\sum_k [\Delta_k/\sigma(r(t_k))]^2$ is not decreased by the new estimate of the $r(t)$ relationship. Studies based on Monte-Carlo and test-beam data show that this autocalibration prodecure provides the $r-t$ relationship with an accuracy of 20 $\mu$m with 1000 tracks which corresponds to a data acquisition time in ATLAS of about 1 hour per calibration zone at a luminosity of $10^{34}$ cm$^{-2}$ s$^{-1}$.

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

The component of the magnetic field parallel to the anode wires of the drift tubes in some chambers at the end of the magnet coils varies by 0.4 T along the tubes. As the Lorentz force bends the electrons drifting to the anode wires, the $r-t$ relationship is altered by the magnetic field along the tubes. In order to be able to perform the autocalibration procedure, the magnetic field dependence of the $r-t$ relationship has to be corrected for. Figure 2 shows how the magnetic field changes $r(t)$ relationship as a function of the muon impact radius. The round points show the test-beam measurement, the crosses the prediction by the Garfield [7] simulation programme. Measurement and simulation agree on the level of 3 ns. An error of 3 ns on the prediction of the change of the maximum drift time corresponds to an error $r(t)$ of about 60 $\mu$m at large radii. It decreases to 10 $\mu$m when measurement and prediction agree on the level of 0.5 ns. The measured magnetic-field depence of $r(t)$ will allows us to improve the simulation to required accuracy of 0.5 ns.

## V. Impact of the High Background Radiation on the Tube Performance

THE neutron and $\gamma$ background in the ATLAS cavern will lead to count rates of up to 500 Hz cm$^{-2}$ (including a safety factor 5) in the MDT chambers. The ions created by the hits in the gas volume of the tubes lead to a space charge in the tubes which lowers the electric field near the anode wires. As a consequence the gas gain is decreased. The gain drops by 9% at the maximum expected background rate of 500 Hz cm$^{-2}$. The reduced gas gain leads to a spatial resolution deminished by 30 $\mu$m for hits near the anode wire of a tube. The fluctuation in time of the space-charge created by the background hits implies a fluctuation in time of the electric field inside tubes. Since Ar:$CO_2$ is a non-linear gas, the fluctuation of the electric field translates into a fluctuation of the $r-t$ relationship. The larger the drift path the more add up the fluctuations. The fluctuation cannot be resolved so that the spatial resolution of the drift tubes is degraded with increasing drift radius and background rate. This behaviour is demonstrated in Figure 3 which contains the radius dependent spatial resolution of a drift tube for different background rates.

Figure 4 shows the quadratic average of the resolution curves which is, by definition, the average single-tube resolution. It does not meet the requirement of a resolution better than 110 $\mu$m. The requirement can, however, be achieved by applying time-slewing corrections using the pulse-height measurements of the front-end electronics. With no background, a resolution of 82 $\mu$m is obtained corresponding to a chamber resolution of 34 $\mu$m in a six-layer chamber; the tube resolution is 108 $\mu$m at 500 Hz cm$^{-2}$ irradiation rate, which corresponds to 45 $\mu$m chamber resolution.

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

THE neutron and $\gamma$ background also leads to a decreased muon detection efficiency. After each hit in a tube, the tube does not detect another hit within the (artificial) dead time of 790 ns after the first hit. Hence a muon is not detected by a tube when it falls into the dead-time window after a preceding background hit. In the test-beam data background hits can be identified by comparing their drift radii $r(t_k)$ with the distances

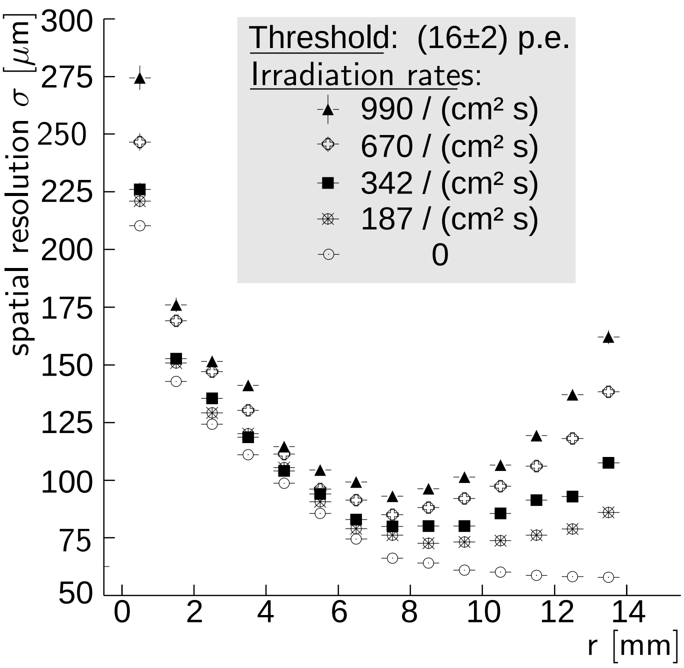


Fig. 3. Spatial resolution curves obtained at different background rates. The discriminator threshold used corresponds to the 16th primary electron.

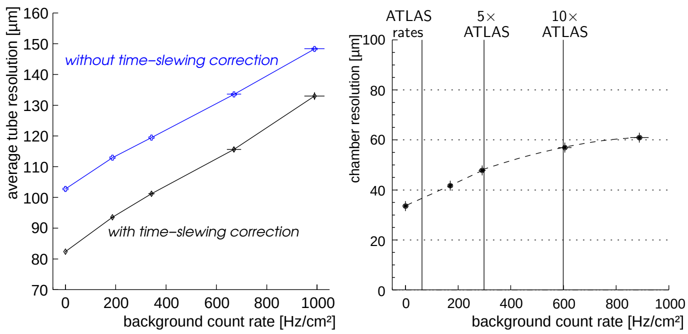


Fig. 4. Left: single-tube resolution with and without time-slewing corrections. Right: spatial resolution of a six-layer chamber.

$d_k$ of the tracks reconstructed with the silicon detectors from the corresponding anode wires. If

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

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

Figure 5 shows the single-tube efficiency as a function of the $\gamma$ background rate. It decreases with increasing background as expected for a dead time of 790 ns. It starts at 94% with no background, at less than 100% because $\delta$ electrons knocked out of the tube walls by the incoming muons can cause hits at radii closer to the anode wires than the muon hits. It decreases to 89% at the maximum count rate expected for the operations of the muon spectrometer at an LHC luminosity of $10^{34}$ cm$^{-2}$ s$^{-1}$. If the safety factor 5 is considered, the efficiency is significantly diminished, namely to 72%. If tracks

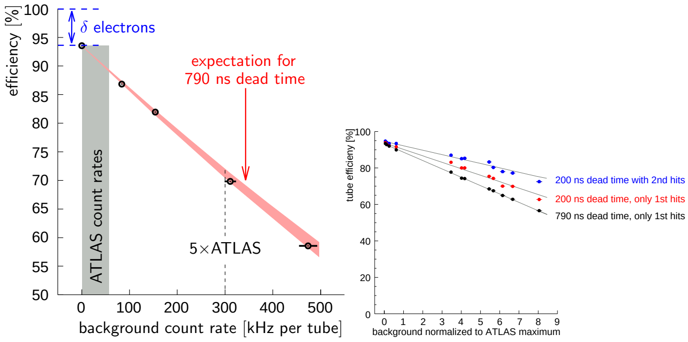


Fig. 5. Left: Single-tube resolution as a function of the background count rate at a dead-time setting of 790 ns. Right: Corresponding tracking efficiency achieved in a six-layer chamber at perpendicular track incidence.

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 5). 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.

A ten times higher background than expected may be encountered in the muon spectrometer after a luminosity upgrade of the LHC to $10^{35}$ $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. In this case, the tracking efficiency will be significantly reduced to about 65%.

## VII. Perspectives for Efficiency Improvements

In order to explore the efficiency limit at very high background rates with the present front-end electronics, data were acquired with the minimum dead-time setting of 200 ns. The data were analysed in two ways:

1) Whenever more than one hit was detected by a tube in an event, the hit first in time was considered. As the dead time is much shorter than the maximum drift time of about 700 ns, the single-tube efficiency is increased (see Figure 6). At a rate of ten times the ATLAS maximum, the efficiency gain is 10%.
2) Whenever the first had 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. 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.

Studies in the early stage of the ATLAS experiment [9] show that the tracking efficiency in the entire muon spectrometer where three chambers are traversed by the muons should also improve. These studies, however, were done based on another (linear) gas mixture and simplifications. The authors of the present article plan to repeat the cited analysis with more realistic assumptions based on the test-beam measurements. The results shown before indicate that the muon chambers and their front-end electronics are capable of the higher rates to be encountered after the LHC luminosity upgrade.

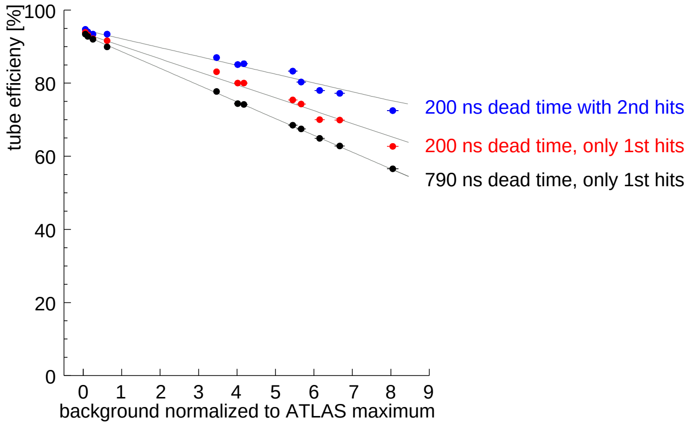


Fig. 6. Muon detection efficiency of a single tube as a function of the $\gamma$ background for different dead-time settings. The dashed line are the results of linear regressions to the measured efficiencies.

## VIII. Conclusions

The drift tube chamber of the ATLAS muon spectrometer are precision tracking detectors able to measure track points with an accuracy better than 45 $\mu$m. The high accuracy is achieved by 20 $\mu$m position accuracy of the sense wires and a knowledge of the space-to-drift-time relationship on the level of 20 $\mu$m or better. We have shown that an autocalibration prodecure using muon tracks in a multilayer of a chamber allows us to recalibrate the $r-t$ relationship with 20 $\mu$m accuracy in a chamber area of 1 $\mathrm{m}^2$ once an hour during the operation at the LHC with $10^{34}$ $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ luminosity. In chambers close to the ends of the magnet coils of the muon spectrometers, the magnetic field varies by up to 0.4 T within an autocalibration zone. In these zones magnetic field corrections based on our test-beam measurements and a Garfield calculation must be applied to the $r-t$ relationship.

The drift-tube chambers will encounter a high neutron and $\gamma$ background in the ATLAS cavern. The spatial resolution of the chambers was shown to be better than 45 $\mu$m even at a background count rate of 500 $\mathrm{Hz\,cm}^{-2}$ which is – including a safety factor 5 – the highest background rate the chambers can encounter during the operation at the LHC. In order to keep the count rates of the chambers within the bandwidth of the whole read-out chain, the tubes are read out with an artificial dead-time of 790 ns. The tracking efficiency of a single chamber turns out to be above 90% for the background count rates of the chamber at the LHC; it stays above 80% if (including the safety factor 5) five times higher rates are encountered.

The chambers are able to cope with even higher rates (800 $\mathrm{kHz\,cm}^{-2}$) if the artificial dead time is reduced to its minimum of 200 ns: a single tube has a muon detection efficiency of 80% at these high rates. This result indicates that increasing the bandwidth of the read-out chain could be a way to operate the muon spectrometer with high performance after the LHC luminosity upgrade to $10^{35}$ $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$.

## ACKNOWLEDGMENT

The authors would like to thank M. Clayton, L. Gatignon, and P. Pierre for providing us the dipole magnet for our studies and A. di Girolamo and M. Kollefrath for lending us equipment. We also want to express our gratitude to T. Christiansen and J. Gregory for helping us in the development of our read-out software.

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