First Results from the Cosmic-Ray Test-Facility at LMU Munich

M. Binder, J. Dubbert, R. Hertenberger, J. Elmsheuser,
O. Kortner, F. Rauscher, M. Rykaczewski, O. Sahr, D. Schaile,
A. Staude, H. Steffens, W. Stiller, V. Zhuravlov, Č. Zupančič
Ludwig-Maximilians-Universität München
Am Coulombwall 1, D-85748 Garching

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Abstract

A cosmic-ray test-stand for MDT chambers has been installed at the University of Munich. Three BOS chambers stacked on top of each other were operated simultaneously. All chambers show proper operational behaviour: in all of their tubes the rate of accidental hits was small and the length of their drift-time spectra agreed within 1.6 ns and better inside each triple layer of tubes. Tracks reconstructed in the uppermost and lowest chamber were used to measure the ATLAS z-coordinate of the anode wires and the distance of the tube layers in the chamber in the middle. Comparisons with the measurement of the x-ray tomograph show that both quantities can be determined with an accuracy of 10 μm after a data-acquisition time of 20 hours.

1 Introduction

The series production of BOS-type MDT chambers started at MPI Munich last year. About 20% of the 88 chambers to be built have been produced so far. These chambers will be tested in a cosmic-ray set-up provided and developed by the University of Munich (LMU). The experimental set-up at LMU allows the measurement of the efficiency, the noise, and the drift-time spectrum of each tube of a chamber. Its design also enables us to verify the geometrical precision of a chamber which is confirmed by the first results presented in this article, but was expected by Monte-Carlo investigations [1].

2 Experimental Set-up

Figure 1 shows a sketch of the cosmic-ray set-up which agrees with the final set-up apart from the fact, that due to lack of enough MDT electronics only a third of the drift tubes could be read out. One triple layer was not read out at all. This triple layer showed a high dark current. An investigation has shown that it was caused by rests of soap on the gas connectors. The soap was originally used to test the tightness of the gas system before it had been mounted onto the chamber. In the meantime this problem has been solved.

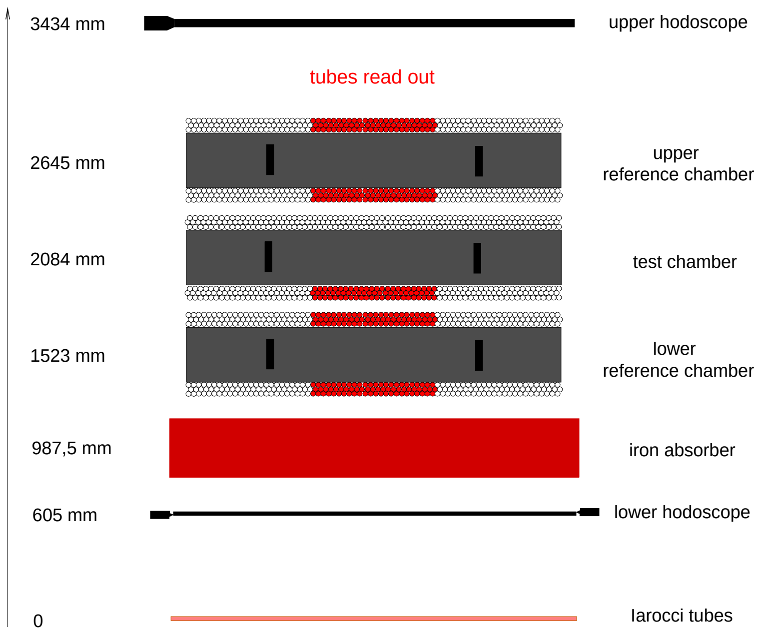

Figure 1: Schematic of the cosmic-ray set-up operated during the measurement presented in the present article. Only the marked drift tubes were read out.

Two reference chambers whose geometry is know from x-ray tomograph measurements enclose a third chamber. The third chamber is to be tested in the stand and will therefore be called test chamber from now on. The reference chambers provide a muon track which is used to verify the mechanical precision of the test chamber. Above the upper reference chamber, 42 scintillation counters, 90 mm wide each, are installed perpendicularly to the drift tubes. They measure a track point along the anode wires of the drift tubes. The lower hodoscope consisting of two layers of two times 38 scintillation counters (100 mm wide each) also gives a track point along the anode wires. As the two layers of scintillation counters are read out on opposite sides one obtains an event time, which is independent of the impact point of the muon in the hodoscope, by averaging over the hit times in the two layers. This event time has a precision of 750 ps. The 34 cm thick iron absorber between the lower reference chamber and the lower hodoscope absorbs all low-energy cosmic rays and all cosmic muons with an energy below 600 MeV. A further hardening of the spectrum is desirable as the energy spectrum of cosmic muons roughly follows a $\frac{1}{E^2}$ rule [2] and peaks at low energies. As the scattering angle of the muon in the test chamber and the scattering angle in the iron absorber depends on the muon energy one can calculate an energy estimate from these two scattering angles. The energy spectrum of the selected muons can then be hardened by a cut on the estimated energy. The scattering angle in the test chamber is obtained by comparing the slopes of the track reconstructed in the upper reference chamber with the slope of the track reconstructed in the lower reference chamber. The scattering angle in the iron absorber is determined by extrapolating the track reconstructed in the lower reference chamber to the plane where the Iarocci tubes are installed and comparing the extrapolated track position with the hit position in the Iarocci tubes.

The Iarocci tubes are read out via 10 mm wide pick-up strips.

In addition to the in-plane alignment sensors of the MDT chambers a system monitoring the position and orientation of the chambers with respect to each other is installed. We devote a separate note [3] to the alignment monitoring system and do not describe it here.

3 Experimental Conditions

The experimental apparatus resides in a air-conditioned hall. Its temperature is 19.5^oC with a maximum fluctuation of $\pm 0.5^oC$. The drift tubes were filled with premixed Ar:CO_2 gas in the mixing ratio 92.58:7.42. The gas pressure was 3.000 bar and stabilized to 2 mbar. The operating voltage of 3160 V corresponds to a gain of $4 \cdot 10^4$ [4]. None of the alignment sensors showed a movement of more than 5 μm during the measurement upon which the results presented in this note are based. So the set-up is considered rigid in the further analysis.

4 Trigger Scheme and Trigger Rate

The data acquisition was triggered if there was a hit in the upper hodoscope and there were two hits in the lower hodoscope. These two hits had to belong to overlapping counters in different scintillator layers. The trigger rate obtained with this scheme is about 300 Hz. As the average read-out time is 4 ms, however, only 150 events a second could be recorded.

In the subsequent sections 10 million events recorded with this trigger are investigated. These events were taken within 20 hours.

5 Analysis Strategy

The stategy of the analysis is: the reference chambers are inspected for their reliability by measuring characteristic parameters of their drift-time spectra; in the second step a space-to-drift-time relationship is determined; tracks reconstructed in the upper and lower reference chamber are then compared in order to find out the position and orientation of the reference chambers relative to each other; finally, after the calibration of the reference part, the test chamber is examined.

6 Calibration of the Reference Chambers

We begin with the calibration of the reference chambers.

6.1 Investigation of the Drift-Time Spectra

A typical drift-time spectrum of one of the tubes in the reference chambers is presented in figure 2. According to the approach described in the reference [7]

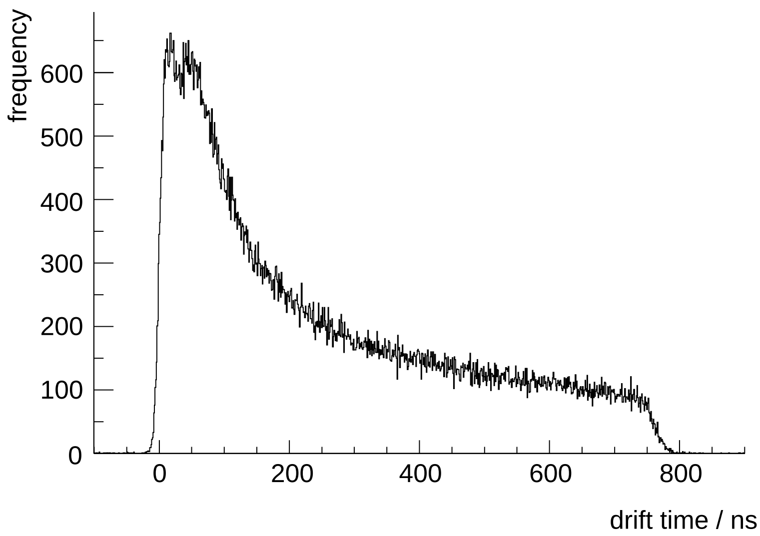

Figure 2: Drift-time spectrum of one of the tubes in the lower reference chamber.

the function

$$G(t) := p_0 + F(t) = p_0 + \frac{A_0}{1 + e^{-\frac{t-t_0}{T_0}}}.$$

is fitted to the left edge of the spectrum, the function

$$H(t) := p_m + \frac{\alpha_m t + A_m}{1 + e^{\frac{t-t_m}{T_m}}}.$$

to the end of the drift-time spectrum. The parameter p_0 gives the number of entries per drift time for drift times less than 0 and measures the absolute frequency of accidental hits. The parameter A_0 reflects the height of the drift-time distribution for times less than 100 ns. Finally the length of the drift-time spectra is given by the difference $t_m - t_0$.

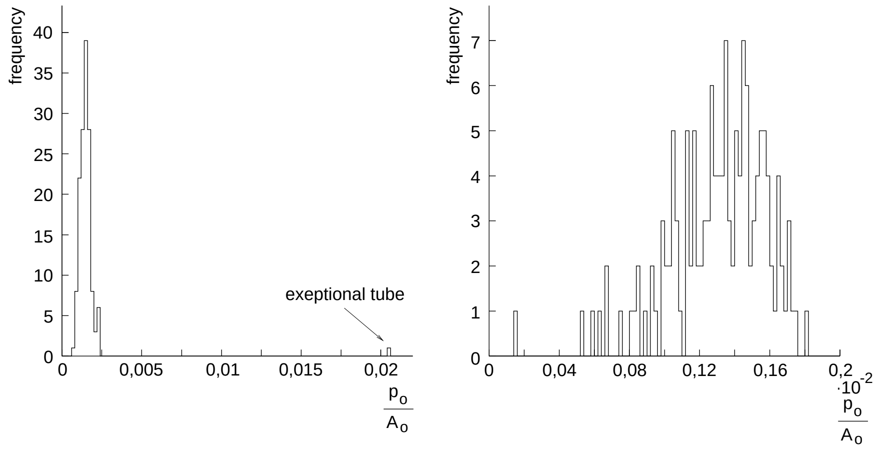

Figure 3: Distribution of the ratio $\frac{p_0}{A_0}$ as a measure for the frequency of accidental hits. The left histogram belongs to the upper reference chamber, the right histogram to the lower.

The ratio $\frac{p_0}{A_0}$ is histogrammed in figure 3 for the drift tubes of both reference chambers. The ratio is of the order of 10^{-3} except for one tube where it is 0,02. This means that essentially all drift-tube hits are caused by the muon triggering the data acquisition. Even in the case of the tube with a higher rate of accidental hits, the accidental rate is still so small as to cause no problem in the track reconstruction.

Since the tubes inside a triple layer all are filled with the same gas mixture at the same pressure, driven at the same high voltage, and uniformely illuminated, their drift-time spectra should have the same length. According to figure 4 the lengths $(t_m - t_0)$ are scattered around their mean by less than 1,8 ns in each triple layer of the reference chambers. The precision of the $(t_m - t_0)$ measurement is 0,8 ns so that the length of the drift-time spectrum fluctuates by less than 1,6 ns within a triple layer. The upper triple layer of the lower reference chamber shows a 7 ns longer drift-time spectrum than the other reference layers. The greater maximum drift time is most probably caused by a slightly different temperature of that particular triple layer which is also indicated by our temperature sensors on this triple layer.

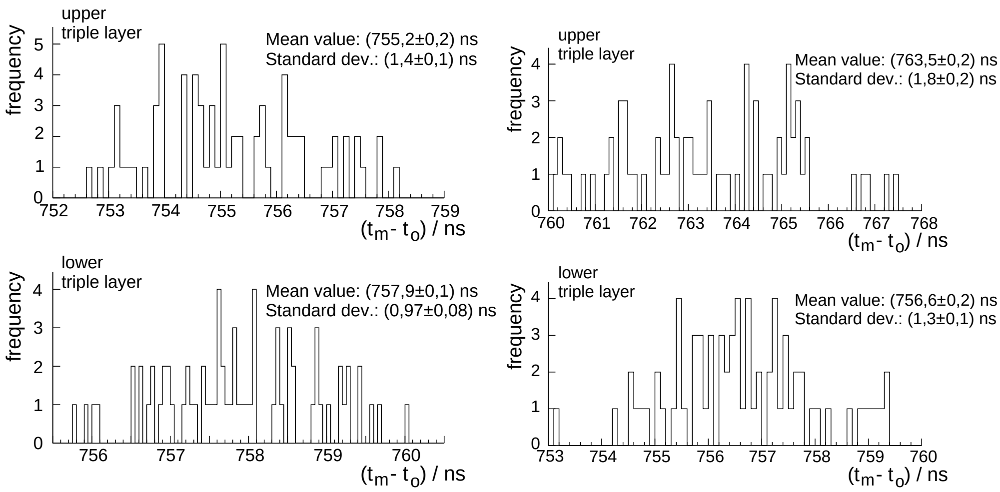

Figure 4: Distribution of the lengths $(t_m - t_0)$ of the drift time spectra in the triple layer of the reference chambers, for the upper chamber on the left, for the lower on the right side.

6.2 Determination of the Space-to-Drift-Time Relationship

The drift-time spectra in the tubes of the upper reference chamber and the lower triple layer in the lower reference chamber have the same length. We shall therefore ascribe a common space-to-drift-time relationship to them. This relationship will also be applied to the upper triple layer of the lower reference chamber after a multiplication of the drift times by $\frac{756,6\ ns}{763,5\ ns}$ to account for the greater maximum drift time.

We determine this common space-to-drift-time relationship with an accuracy of 25 μm by selecting events in which the muon hits a wire in the lowest tube layer of the upper reference chamber and a wire in the uppermost layer of that chamber. In this case the muon track is uniquely defined by these two wire hits and we can calculate the distance r of this track from the anode wire in the inner layers. In the inner layers drift times are measured so that points (r, t) are obtained. We finally end up with 18 base points which are almost uniformely distributed in r. Between the base points we assume the space-to-drift-time relationship to be linear.

6.3 Relative Alignment of the Reference Chambers

The knowledge of the space-to-drift-time relationship allows us to separately reconstruct tracks in the upper and lower reference chamber. A misalignment of the reference chambers with respect to each other lets the upper reference track systematically deviate from the lower reference track. One can extract the position and orientation of the reference chambers relative to each other from these deviations. The misalignments which must be measured that way are depicted in figure 5. With half of the collected events we resolved the horizontal displacement

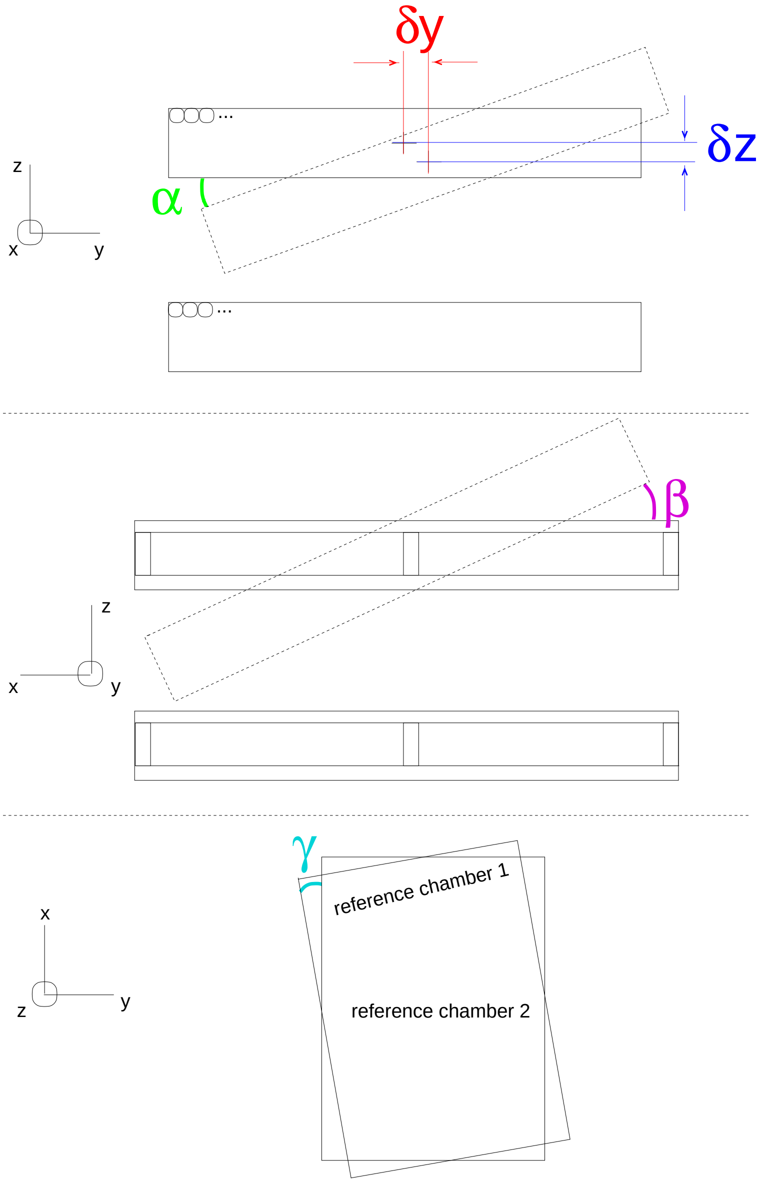

Figure 5: Possible misalignment of the upper and lower reference chamber which has to be resolved. The coordinate frame drawn here does not follow the ATLAS naming conventions.

δ_y with an accuracy of 4 μm, the vertical displacement δ_z with an accuracy of 30 μm, and the rotations α, β, and γ with an accuracy of $7 \cdot 10^{-6}$, $4 \cdot 10^{-5}$, and

$4 \cdot 10^{-6}$ respectively.

The procedure to determine α, β, γ, δ_y, and δ_z is described in [3] in detail. Here were just want to present the results. If $m_{y,up}$ denotes the slope of the upper reference track in the yz plane and $m_{y,up}$ denotes the corresponding slope of the track reconstructed in the lower reference chamber, α is the mean value of $m_{y,down} - m_{y,up}$. If the intercepts of the upper and lower reference tracks in the yz plane are $b_{y,up}$ and $b_{y,down}$, δ_y is the mean value of $b_{y,down} - b_{y,up}$. δ_z is the slope of the straight line which is obtained when one plots $b_{y,down} - b_{y,up}$ versus $m_{y,down}$. Accordingly, γ is obtained as the slope of the straight line which is obtained when one plots $b_{y,down} - b_{y,up}$ versus the position of the muon track along the wire. Finally, β can be calculated from δ_z at the two end of the chambers.

7 First Inspection of the Test Chamber

After the calibration of the reference part we turn to the test chamber.

We first inspect the drift-time spectra of its tubes. The ratio $\frac{p_0}{A_0}$ is less than 0,05 in all the tubes, accidental hits are rare. The length of the drift-time spectra fluctuates by 1,1 ns. The test chamber showed stable operational behaviour.

The drift-time spectra in the test chamber are 753,9 ns long on the average, hence as long as the spectra in the upper reference chamber. So, the same space-to-drift-time relationship can be used to reconstruct tracks in the test chamber. The comparison of these tracks with the reference tracks yield the position and orientation of the test chamber inside the reference part.

8 Measurement of Wire Positions in the Test Chamber

We mentioned in the introduction that the design of the cosmic-ray set-up allows the measurement of the coordinates of the anodes wire in the test chamber. We begin with preparatory considerations which clarify how this goal can be achieved. After this introductory part we will compare the results of our measurement with the results from the x-ray tomograph at CERN [5].

8.1 Preparatory Considerations

If an anode wire sits in its nominal position $(0,0)$ the drift radius r_d measured by a tube which is hit by a muon equals the distance r_t of the muon track from the anode wire within the statistical precision. If the equation

$$y = mz + b$$

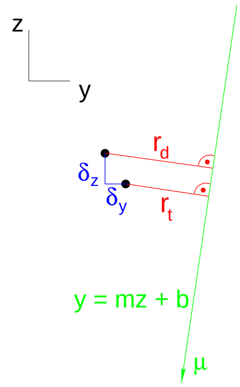

Figure 6: Muon track hitting a tube with a displaced wire. The coordinate frame drawn here does not follow the ATLAS naming conventions.

holds for the muon track, as sketched in figure 6,

$$r_t = \frac{|b|}{\sqrt{1+m^2}}.$$

Once the wire is displaced from its nominal position by (δ_y, δ_z) the drift radius becomes

$$r_d = \frac{|b - \delta_y + m\delta_y|}{\sqrt{1+m^2}}.$$

The comparison of r_t and r_d yields

$$r_t - r_d = \frac{\delta_y - m\delta_z}{\sqrt{1+m^2}}$$

for muons which pass the wire on the right and

$$r_t - r_d = \frac{m\delta_z - \delta_y}{\sqrt{1+m^2}}$$

for muons which pass the wire on the left. $r_t - r_d$ contains the information about the wire displacement (δ_y, δ_z).

The reconstructed tracks have different slopes. One must average over them. The averaging process is particularly advantageous if the slopes of the collected muons are distributed symmetrically around 0. In this case the mean value of $r_t - r_d$ does not depend on δ_z because the average of $\frac{m}{\sqrt{1+m^2}}$ vanishes. We then have

$$< r_r - r_d >= \pm \left\langle \frac{1}{\sqrt{1+m^2}} \right\rangle \delta_y.$$

At the cosmic-ray stand the slopes are in the range [-0.38, 0.38], $\left\langle \frac{1}{\sqrt{1+m^2}} \right\rangle = 0.95$. Hence the factor $\left\langle \frac{1}{\sqrt{1+m^2}} \right\rangle$ can be set to 1.

After the determination of the horizontal displacement we are able to find out the vertical displacement δ_z. For muons passing the wire on the left we get

$$r_t - r_d = -\frac{m}{\sqrt{1+m^2}}\delta_z,$$

and for muon passing the wire on the right

$$r_t - r_d = \frac{m}{\sqrt{1+m^2}}\delta_z.$$

We define

$$\Delta_r := \begin{cases} r_d - r_t \text{ for muons passing on the left,} \\ r_t - r_d \text{ for muons passing on the right.} \end{cases}$$

Plotting Δ_r as a function of m gives a straight line with the slope δ_z since

$$\Delta_r = \delta_z \frac{m}{\sqrt{1+m^2}} \approx \delta_z \cdot m.$$

8.2 Measurement of the Horizontal Wire Displacement

Wire displacemenst can only be determined if the space-to-drift-time relationship in the tubes of the test chamber is known. In the case of horizontal displacements one can elegantly combine the determination of the space-to-drift-time relationship with the displacement measurement itself. One introduces a signed distance of the muon track from the wires. If a track passes an anode wire on the right hand side of its nominal position one gives it a positive sign; if it passes the anode wire on the left hand side one gives it a negative sign. One then plots the drift time measured in the hit tube versus the signed distance of the track from the anode wire of the tube. One obtains a v-like distribution as presented in figure 7. The position of the minimum of the v equals the horizontal displacement of the anode wire. The v plot is symmetric about the horizontal wire position r_0. A fit of a function like

$$f(r) := \sum_{k=0}^{k=n} \alpha_k |r - r_0|^k$$

with the free parameters α_k and r_0 to the v distribution will provide the wire position r_0 and the space-to-drift-time relationship in one go.

We chose $n = 7$ for our measurements but reensured ourselves that the choices $n = 6$, $n = 8$, and $n = 9$ did not change the results. We only considered the central eight tube in each layer of the test chamber because the slopes of the tracks which hit these tubes are symmetrically distributed about 0.

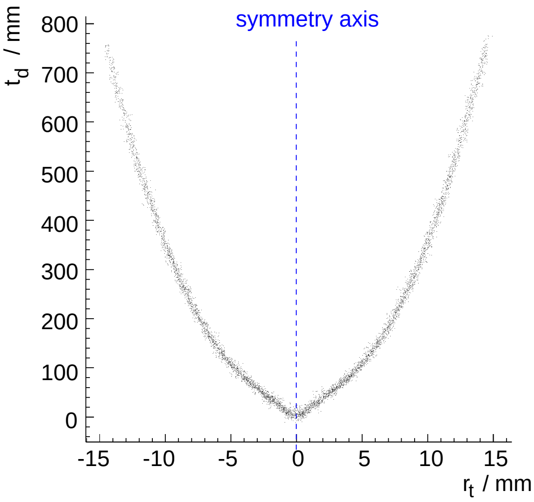

Figure 7: Drift time in a tube of the test chamber as a function of the signed distance of the muon from its anode wire. Entries from δ electrons have been removed.

In order to reduce the influence of multiple scattering on our r_t measurement we rejected all events in which our estimate of the muon energy was less than 2,5 GeV. This energy estimate was obtained from the scattering angle of the muon trajectory in the test chamber and the scattering angle in the iron absorber.

Although all three chambers had been x-rayed in the tomograph we only used the tomograph geometry for the reference chambers; we assigned the nominal geometry to the test chamber. However, the tomograph measurement of the test chamber [6] enables us to judge the quality of our displacement measurement. Figure 8 shows a comparison of the tomograph measurement and our measurement for 1m of the tubes in the middle of the chamber. If D is the horizontal distance of the wires in two neighbouring tubes of a layer we define

$$\Delta_h := D_{measured} - D_{nominal}$$

where $D_{measured}$ is the measured distance D and $D_{nominal}$ is the nominal distance. Our measurement of Δ_h with the cosmic-ray stand is correlated with the tomograph measurement. The distribution of $\Delta_{h,teststand} - \Delta_{h,tomograph}$ peaks at 0. Its mean value is compatible with 0 and its standard deviation equals (10 ± 2) μm.

8.3 Measurement of the Interlayer Distance

In order to measure the distance of the tube layers we plotted Δ_r versus the track slope m for the eight tubes considered per layer. We obtained three straight lines whose slopes equal the vertical displacement of the layers (see figure 9). From these we calculated the interlayer distance: we measured (26.022 ± 0.010) mm for the distance of the uppermost and the middle layer, the tomograph measured

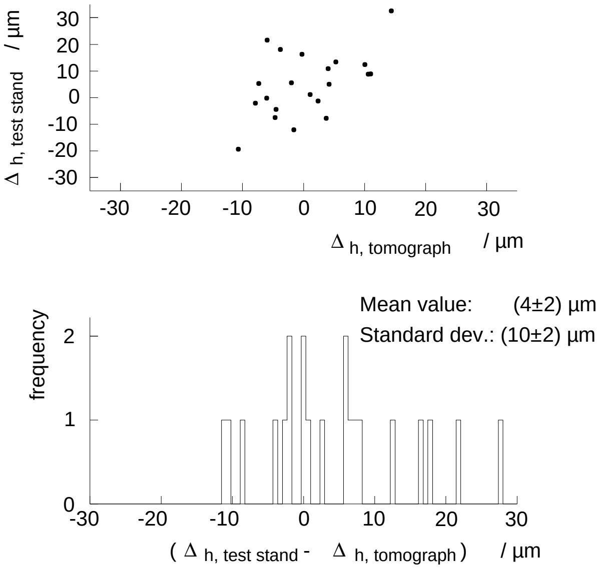

Figure 8: Comparison of the measurement of the horizontal wire spacing by the cosmic-ray stand and the x-ray tomograph.

(26.018 ± 0.003) mm; we measured (26.051 ± 0.010) mm for the distance of the middle layer and the lowest layer, the tomograph measured (26.046 ± 0.003) mm. Our result agrees with the tomograph result within the errors and deviated from it by less than 10 μm.

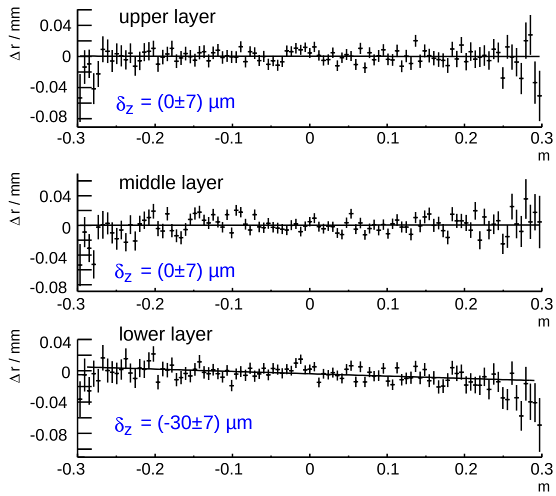

Figure 9: Δ_r as function of the track slope m.

9 Summary

The cosmic-ray test-stand installed at the Ludwig-Maximilians-Universität is an excellent device for testing the ATLAS muon chambers. It does not only allow a test of the functionality of the chambers but also the verification of its mechanical precision as confirmed by the comparison of test-stand results with the measurement of the x-ray tomograph. Horizontal displacements of a single anode wire can be measured with an accuracy of (10 ± 2) μm averaged over 1 m of wire with the data collected in 20 hours of data taking. With the same data the distance of two layers of eight tubes each can be measured with an accuracy of 10 μm per metre of tube.

Acknowledgements

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