Preprint typeset in JINST style - HYPER VERSION

Not reviewed, for internal circulation only

Tracking and Level-1 triggering in the forward region of the ATLAS Muon Spectrometer at sLHC

J. Dubbert, H. Kroha, R. Richter*and P. Schwegler

Max-Planck-Institute for Physics, Munich, Germany

E-mail: richterr@mpp.mpg.de

ABSTRACT: In the endcap region of the ATLAS Muon Spectrometer ($\eta > 1$) precision tracking and Level-1 triggering are performed by different types of chambers. Monitored Drift Tube chambers (MDT) and Cathode Strip Chambers (CSC) are used for precision tracking, while Thin Gap Chambers (TGC) select high-p_T muons and form the Level-1 muon trigger. When by 2018 the LHC peak luminosity of $10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ will be increased by a factor of ~ 2 and by another factor of ~ 2–2.5 in about a decade from now (”SLHC”), an improvement of both systems, precision tracking and Level-1 triggering, will become mandatory in order to cope with the high rate of uncorrelated background hits ("cavern background") and to stay below the maximum trigger rate for the muon system, which is in the range of 10–20 % of the 100 kHz rate, allowed for ATLAS.

For the Level-1 trigger of the ATLAS Muon Spectrometer this means a tighter selection of high-p_T muons as well as a better rejection of tracks not coming from the primary interaction point (IP). Both requirements, however, can only be fulfilled if spatial resolution and angular pointing accuracy of the trigger chambers, in particular of those in the Inner Station of the endcap, are improved by a large factor. This calls for a complete replacement of the currrently used TGC chambers by a new type of trigger chambers with better performance. In parallel, the precision tracking chambers must be replaced by chambers with higher rate capability to be able to cope with the intense cavern background.

In this article we present concepts to decisively improve the Level-1 trigger with newly developed trigger chambers, being characterized by excellent spatial resolution, good time resolution and sufficiently short latency. We also present a new type of MDT precision chamber, designed to maintain excellent tracking efficiency and spatial resolution in the presence of high levels of uncorrelated background hits, as generated by γ and neutron conversions.

KEYWORDS: Muon spectrometers; Particle tracking detectors (Gaseous detectors); Large detector systems for particle and astroparticle physics .

*Corresponding Author

Not reviewed, for internal circulation only

Contents

1. Introduction

While peak luminosities at the SLHC will be 4–5 times higher compared to the LHC design luminosity of $10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, the Level-1 trigger rate will have to remain at about 100 kHz. For this to happen the trigger selectivity for muons with high transverse momentum (p_T) has to be improved, the p_T distribution of muons falling off strongly with increasing p_T. Total muon cross sections above p_T values like 10, 20 and 40 GeV are 734, 47 and 3 nb, respectively (cf. [1]).

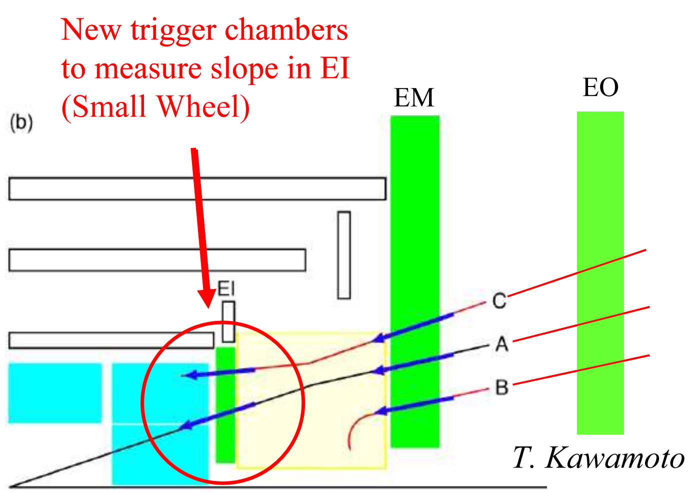

Figure 1. Three trigger scenarios in the EI station of the Muon spectrometer ("Small Wheel"). Tracks B and C may generate a fake trigger, without originating from the primary vertex.

Many interesting physics processes with small cross sections have a signature of one (or more) muons above ~ 20 GeV. The capability to trigger on high-p_T tracks was therefore one of the principal requirements for the design of the ATLAS muon spectrometer [2, 3]. For this purpose a system of trigger chambers was implemented, covering the full acceptance of the muon detector, capable to detect tracks above a predefined p_T within a sufficiently short latency to be used in the ATLAS Level-1 trigger. In the barrel and endcap regions different chamber technologies were chosen, adapted to the different configurations of the magnetic field in these detector domains.

In this article we describe the endcap region, where recent LHC running has shown a high level of fake triggers.

The TGC trigger chambers in the middle endcap station (EM) measure the slope of the muon tracks. Only tracks pointing closely to the primary vertex are selected for the Level-1 trigger, assuming they only had undergone a small deflection in the magnetic field of the endcap toroid. At the Inner station (EI), however, no measurement of the slope is presently available. The consequences of this default for the trigger selectivity are demonstrated in Fig. 1, where three scenarios of muon tracks are shown which generate triggers in the present system: track A corresponds to a valid high-p_T muon trigger candidate, the small angular deviation from an infinite momentum line being the criterion for high-p_T, while tracks C and B do not come from the IP, being either scattered in the calorimeter (C) or having its origin in the down-stream region and being deflected "backwards" by the toroidal magnet. Obviously, fake triggers of type B and C could be rejected by a precise measurement of the track's slope in the EI station.

While this is one of the main requirements for an improvement of the Level-1 trigger, the presently used precision chambers will also need to be improved, in order to maintain high tracking efficiency in the presence of the high background hit rates expected for the endcap region.

The present concept for the upgrade is a complete replacement of the EI stations with new trigger and precision chambers, as presented below.

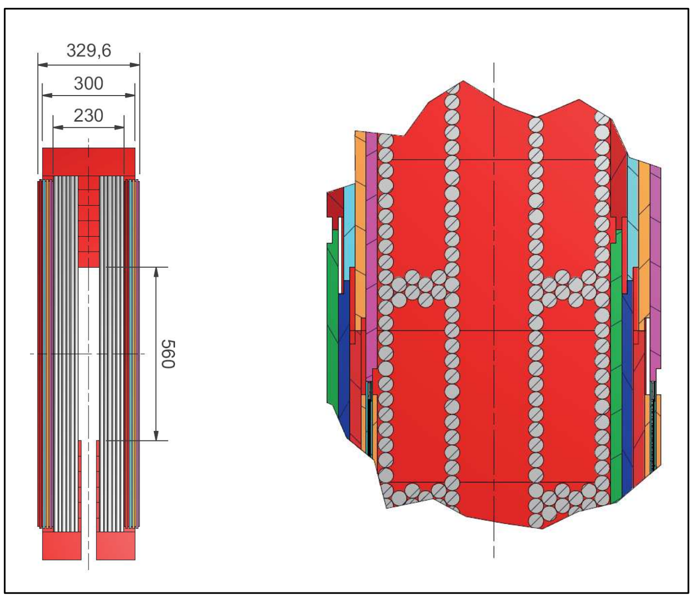

Figure 2. Cross section through the proposed arrangement of trigger TGCs and precision MDTs. The MDT, made out of two multilayers (with 4 or 6 tube layers) is sandwiched between two packages of 4-layer TGCs. The outer distance of 300 mm between the TGC packages is instrumental for the angular resolution of the triggering muon track.

Not reviewed, for internal circulation only

2. Concept for a new Inner Station in the endcap of the Muon Spectrometer

Presently three concepts are considered as candidates for an improved trigger in the EI station: (a) Thin Gap Chambers (TGC), (b) Resistive Plate Chambers (RPC) and (c) Micromega Chambers (MM), the latter combining precision tracking and triggering capabilities in the same chamber. All three chamber types achieve a position resolution accuracy of < 0.2 mm in the radial coordinate η. For precision tracking Small tube MDT chambers (sMDT) and Micromega chambers are under consideration.

In this article we only present the combination of sMDT chambers with the new types of TGC or RPC trigger chambers. This limitation is motivated by the available space and does not imply that the MM concept is considered less suited for triggering and/or tracking.

The requirement for the accuracy of the slope measurement for the trigger in the new EI station is to be better than 1 mrad. The distance between the trigger chamber packages being about 280 mm, a position resolution of < 0.28 mm is therefore required.

2.1 Combined TGC plus sMDT chambers for the Inner Station of the endcap

Fig. 2 shows the concept of combining TGC trigger and sMDT precision chambers in the new EI station ("Small Wheel"). Two sMDT units with 4 or 6 tube layers each, separated by a spacer, are enclosed by two packages of TGCs. Each TGC package consists of four gas volumes with wires in radial direction, with 6 mm spacing, grouped appropriately to give the required granularity for ϕ readout. Among the two cathode planes of each gas volume, one is equipped with pick-up strips, perpendicular to the wires with a pitch of 3.5 mm, measuring η, the other one is segmented in square pads with a size of 7 to 25 cm, depending on R, arranged in projective towers across the chamber layers. A 3-out-of-4 coincidence of the pads in a tower is used to produce a RoI for the Level-1 trigger logic. The pads are also used offline to resolve ambiguities when a chamber contains more than one track.

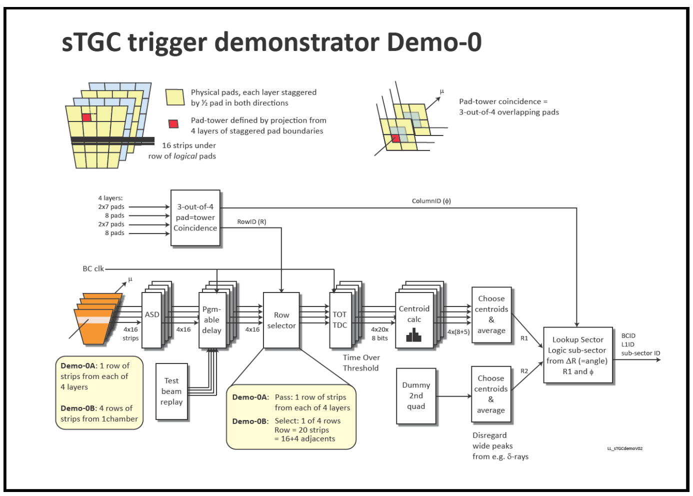

Figure 3. Block diagram of the sTGC trigger as presently implemented in an FPGA demonstrator.

The required position resolution is obtained by a convolution of the pulse heights on adjacent strips, giving the centroid of the charge distribution. Tests under realistic conditions have shown that the pulse heights obtained from a time-over-threshold (ToT) measurement, combined with a fast convolution methode yield the position of the track with an accuracy of $\sim 60\,\mu m$.

In the next step of trigger formation the reconstructed hit positions are combined (after possibly removing spoiled hits [1]), to produce a unique track position in the package. Subsequently, the track positions in the two packages are combined to determine the slope. Finally, a test is made on whether the track points to the interaction point with sufficient accuracy. The result is transferred to the Sector Logic (SL) in USA15, where the trigger decision is made by combining the information from both trigger stations, EI and EM. [2]

Fig. 3 shows a block diagram of the envisaged readout electronics. It is currently implemented in a demonstrator for a detailed evaluation of the resulting trigger latency. For the first phase of the LHC upgrade the maximum Level-1 latency in ATLAS must be below 2.55 μs, counted from the beam crossing to the arrival of the Level-1 trigger at the frontend of the detector electronics. For the sTGC trigger this means that the signals from the chamber frontend must arrive at the input of the Sector Logic not later than 1.05 μs after the collision at the interaction point. Present estimates for the latency of the TGC trigger lead to 0.91 μs, leaving a safety margin of about 150 ns.

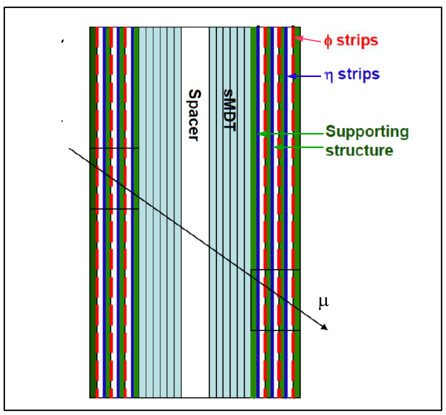

Figure 4. Cross section through the proposed arrangement of trigger RPCs and precision sMDTs. The distance of 280 mm between the RPC packages (center-to-center) is instrumental for the angular resolution of the triggering muon track.

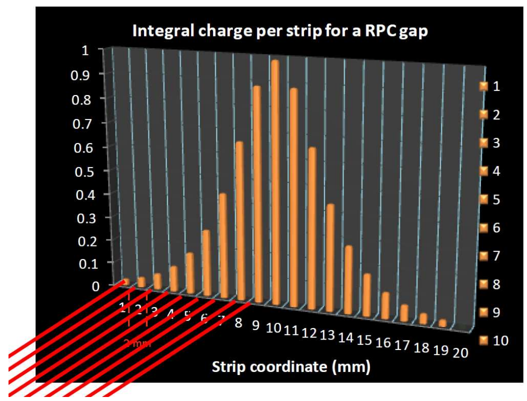

Figure 5. Simulated charge distribution on the pick-up strips of a RPC with ~ 2 mm readout pitch. A convolution of the pulseheights above threshold yields the position of the track with a ~ 0.2 mm accurancy.

2.2 Combined RPC plus sMDT chambers for the Inner Station of the endcap

A similar structure like in the previous chapter can be implemented by combining RPCs with sMDTs (Fig. 4). Again, two sMDT units with 6 tube layers each are sandwiched between two packages of trigger chambers, each having three RPC gas gaps. Each gas gap has pick-up strips in η and ϕ with 1–2 mm and a few cm spacing, respectively. Signals are combined to form 2-out-of-3 coincidences in a similar way like in the case of the sTGC. The signal amplitudes on the strips will have a distribution as illustrated in Fig. 5. A convolution delivers the charge centroid with

[1] Hits may be spoiled by δ rays or neutron conversions, both leading to a wider signal distribution across the strips than is expected for a minimum ionising particle.

[2] The Outer Endcap station (EO) does not contribute to the trigger, containing only MDT precision chambers.

an accuracy of ~ 0.2 mm. The inherently good time resolution of RPCs of < 2 ns allows for an efficient suppression of background hits.

2.3 MDT chambers with Small Tubes for tracking at high background rates (sMDT).

The limitations of the MDT precision chambers at high luminosities at the SLHC are mainly due to isolated hits in the tubes (”fake hits”), caused by Compton scattering of gammas which, in turn, come from neutron capture in the material of the chambers and adjacent support material. In the Small Wheel the resulting hit densities strongly increase towards the inside, while, on the other hand, the length of the tubes in the trapezoidal geometry of the Small Wheel decreases proportional to the distance from the beam line (R). Hit densities, however, are increasing considerably faster than with 1/R, and therefore the highest tube hit rates are at the innermost radii of the chambers.

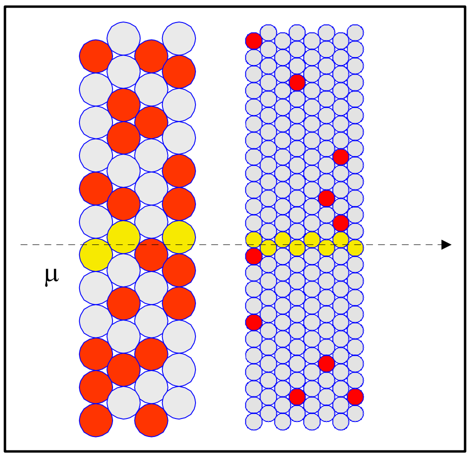

Figure 6. The tracking quality in 30 mm and 15 mm drift tubes. The occupancies from background hits (red dots) are 50% in the 30 mm tubes but only 7% in the 15 mm tubes due to shorter drift time and smaller area.

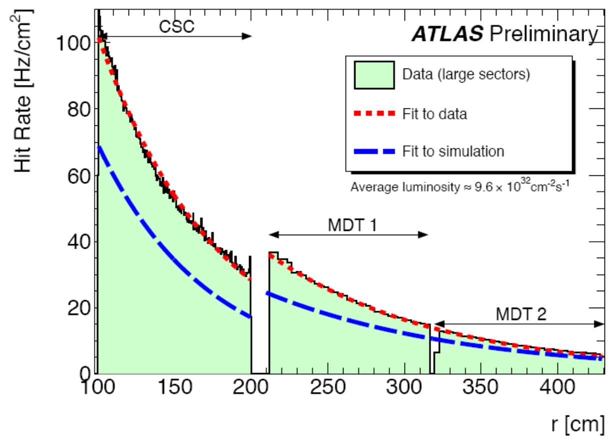

Figure 7. Hit rate per cm^2 in the Small wheel vs. distance r from the beam line at $\sim 10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The change in chamber technology from MDT to CSC at ~ 200 cm leads to a change in normalization of $\sim 10\%$. Simulation slightly underestimates the measured rates (from [4]).

Reduction of the drift tube diameter from 30 mm to 15 mm, while keeping the other parameters unchanged (gas composition, gas gain and sense wire diameter) leads to a significant improvement of the rate capability of the drift tube chambers [5], more than sufficient for their operation in the New Small Wheel (NSW) up to the highest background rates expected at 5 times the LHC design luminosity (see Fig. 6).

Table 1 presents tube hit rates, occupancies and efficiencies for the innermost tubes of the three chamber types in a sector of the NSW. Chamber EIL0 covers the area now taken by the CSC. The numbers in col. 5 are based on hit rate measurements in ATLAS, at a luminosity of $9\cdot 10^{32}$ $\mathrm{cm}^{-2}\mathrm{s}^{-1}$, scaled up linearly to $5\cdot 10^{34}$ $\mathrm{cm}^{-2}\mathrm{s}^{-1}$. Rates in the CSC region (1 m<R<2 m) are measured as well as extrapolated from larger radii, using an exponential law [4]. In addition, these rates have been multiplied by a safety factor of 1.4, which brings the maximum hit rate expected for a tube in the NSW up to 14 kHz/cm^2. The efficiencies are calculated from exp($-\tau\cdot$f) $\approx$ 1-$\tau\cdot$f, where τ is the dead time after a hit (we use the maximum drift time of 200 ns) and f the hit rate per tube.

Chamb. type	Tube layers	Location in r	Tube length	Expected hit rate	Count rate per tube	Occup-ancy	Tube effi-ciency	Segment efficiency
		cm	*cm*	*Hz/cm*^{2}	*kHz*	*%*	*%*	*%*
EIL0	2×6	93	56	14000	1176	23,5	79,0	99.8
EIL1	2×4	208	125	5150	965	19,3	82,4	99.9
EIL2	2×4	318	179	1978	530	10,6	90,0	99.9

Table 1. Expected hit rates and efficiencies for 15 mm tubes in a large sector of the New Small Wheel at a luminosity of 5 × nominal (times a factor of 1.4, see text).

Being able to use the MDT tracking concept at very high background rates allows to preserve the main advantages of the drift tube concept:

(a) Robust pattern recognition and high tracking efficiency up to the expected high backround rates.

(b) Excellent position and angular resolution, independent of the angle of incidence onto the chamber plane. This property of drift tube chambers with their *circular* drift geometry is a decisive advantage over drift chambers with *rectangular* drift geometry.

(c) High reliability of the chambers, due to operational independence of the drift tubes, any malfunction of an individual tube causing only a negligible inefficiency.

(d) Modularity and mechanical robustness of chamber construction.

(e) Direct transfer of the high intrinsic mechanical precision of the chambers at the level of 20 μm to the global optical alignment system, as is already achieved in the present Small Wheel.

Parameter	**Design value**
Tube material	Aluminum
Outer tube diameter	15 mm
Tube wall thickness	0.4 mm
Wire diameter & material	50 μm of gold-plated W/Re (97/3)
Gas mixture	$Ar/CO_2/H_2O$ (93/7/$\leq$ 1000 ppm)
Gas pressure	3 bar (absolute)
Gas gain @ HV	2 x 10^4 @ 2730 V
Maximum drift time	$\sim$ 185 ns

Table 2. The operating parameters of Small Tube MDT chambers.

For the standard MDT gas mixture of $Ar:CO_2$ (93:7) at 3 bar absolute pressure, the gas gain of $2 \cdot 10^4$ is achieved at an operating voltage of 2730 V for 15 mm diameter drift tubes (Table 2). Under these operating conditions, the maximum drift time is reduced by a factor of 3.5 from about 700 ns to $<$ 200 ns [6]. In addition, the background flux, hitting a tube of given length is reduced by

Not reviewed, for internal circulation only

a factor of two. Altogether, the drift tube occupancy is reduced by a factor of 7. At a background rate of 14 kHz/cm^2 the highest occupancy is 23%, corresponding to a counting rate of 1176 kHz (cf. Table 1). The 2×6 drift tube layers at radii $R < 2$ m and the 2×4 layers at larger radii provide very robust tracking with track segment reconstruction efficiencies above 99 % up to the highest background rates [7]. In this configuration, the point and angular resolution of the drift tube chambers will be uniformly 45 μm and 0.5 mrad, respectively, compared to 40 μm and 0.45 mrad without background irradiation.

The mechanical structure and the alignment system will be as similar as possible to the ones in the present Small Wheel architecture. Like in the case of the trigger chambers, new readout electronics with higher rate capabilities will have to be installed.

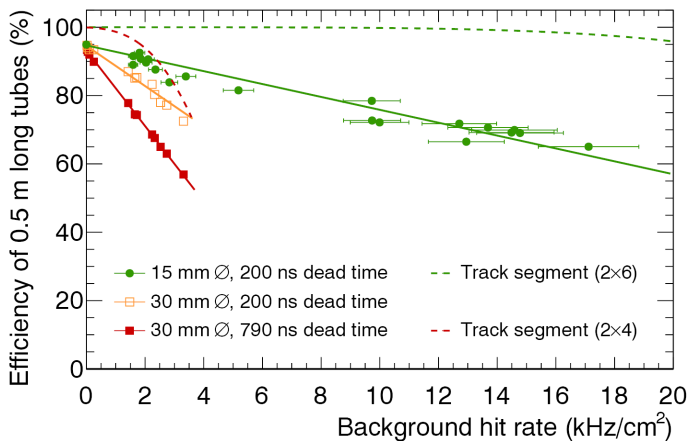

Figure 8. The efficiency of individual drift tubes as a function of the background hit rate as measured at the Gamma Ray Facility at CERN. Results for 15 mm and 30 mm diameter tubes are compared. The corresponding track segment reconstruction efficiencies in 2×4 layer MDT chambers (30 mm tubes) and 2×6 layer sMDT chambers (15 mm tubes) are indicated as dashed curves and have been calculated from the tube efficiencies, requiring at least two hits in each multilayer.

3. Summary

The upgrade of the LHC towards five times the original target luminosity of $10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ calls for a complete replacement of the Inner muon station of the ATLAS endcap ("Small Wheel") as Level-1 trigger rates in the present system will exceed acceptable levels by a large factor, while the tracking efficiency of precision chambers will suffer from high occupancies from γ and n background. Due to the availibility of recently developed concepts for trigger as well as tracking chambers the requirements of the SLHC upgrade can be matched. Concerning trigger chambers, all proposed concepts provide improvements of the spatial resolution by more than an order of magnitude, improving the pointing accuracy of tracks towards the primary vertex to below 1 mrad. Small tube MDT precision chambers, on the other hand, will be able to provide robust tracking up to the highests background rates, due to a reduction of the tube diameter and an increase of the number of tube layers from 8 to 12 at the inner boundary of the Small Wheel. All systems, however, face the challenge of developing new high rate readout electronics on the tight time scale of phase I of the LHC upgrade.

References

[1] J. Dubbert, S. Horvat, O. Kortner, H. Kroha, R. Richter, *Upgrade of the ATLAS Muon Trigger for the SLHC*, *JINST* **5** C12016 (2010)

[2] ATLAS Collaboration, *Technical Design Report for the ATLAS Muon Spectrometer*, CERN/LHCC/97-22, May 1997.

[3] The ATLAS collaboration, *The ATLAS Experiment at the CERN Large Hadron Collider*, JINST **3** S08003 (2008)

[4] L. Jeanty and the ATLAS collaboration, *ATLAS: Data and MC Comparisions for Muon Spectrometer, including Cavern Background*, LPCC Simulation Workshop, October 2011, https://indico.cern.ch/conferenceOtherViews.py?view=standard&confId=144956

[5] B. Bittner, J. Dubbert, S. Horvat, M. Kilgenstein, O. Kortner, H. Kroha, F. Legger, R. Richter, P. Schwegler, S. Adomeit, O. Biebel, A. Engl, R. Hertenberger, F. Rauscher and A. Zibell, *Development of Precision Muon Drift Tube Detectors for the High-Luminosity Upgrade of the LHC*, Nucl. Phys. B (Proc. Suppl.) **215** (2011) 143.

[6] B. Bittner, J. Dubbert, O. Kortner, H. Kroha, F. Legger, R. Richter, O. Biebel, A. Engl, R. Hertenberger and F. Rauscher, *Development of muon drift-tube detectors for high-luminosity upgrades of the Large Hadron Collider*, Nucl. Instr. and Meth. **A617** (2010) 169.

[7] B. Bittner, J. Dubbert, S. Horvat, O. Kortner, H. Kroha, F. Legger, R. Richter, S. Adomeit, O. Biebel, A. Engl, R. Hertenberger, F. Rauscher and A. Zibell, *Development of fast high-resolution muon drift-tube detectors for high counting rates*, Nucl. Instr. and Meth. **A 628** (2011) 154.