Development of Precision Drift Tube Detectors for Very High Background Rates at the Super-LHC

J. Dubbert, S. Horvat, H. Kroha, F. Legger, O. Kortner, R. Richter, F. Rauscher

***Abstract*—The muon spectrometer of the ATLAS experiment at the Large Hadron Collider (LHC) is instrumented with three layers of precision tracking detectors each consisting of 6 or 8 layers of pressurized aluminum drift tubes of 30 mm diameter. The magnetic field of the spectrometer is generated by superconducting air-core toroid magnets. Already at the LHC design luminosity of 10^{34} cm^{2}s^{-1}, the ATLAS muon chambers have to cope with unprecedentedly high neutron and gamma ray background rates of up to 500 Hz/cm^2 in the inner and middle chamber layers in the forward regions of the muon spectrometer. At a high-luminosity upgrade of the LHC (S-LHC), the background rates are expected to increase by an order of magnitude. The resulting high occupancies lead to a significant deterioration of the muon detection efficiency compromising the physics goals. The possibility to improve the muon detection efficiency by reducing the diameter of the drift tubes, and consequently lowering the dead time of the readout electronics, has been investigated. We report about the design and test results of prototype drift-tube detectors with thin-walled aluminum tubes of 15 mm diameter.**

I. Introduction

The Large Hadron Collider (LHC) at CERN will ultimately collide beams of protons at a center-of-mass energy of $\sqrt{s} = 14$ TeV. The first LHC proton beams are expected to be delivered in mid 2008, and stable running conditions of the accelerator and nominal luminosity are expected to be reached 2–3 years after LHC startup. An upgrade of the accelerator luminosity beyond its nominal value, 10^{34}cm^{2}s^{-1}, is already under discussion, and it may ultimately lead to increase the nominal LHC luminosity by an order of magnitude, over a long term (years of operation) [1].

In the first phase (expected in the period 2009-2015), a stretching of the machine parameters up to their limits may lead to a luminosity increase of about a factor 2.3. Later phases foresee an upgrade of the interaction regions, leading to stronger focussing (around 2015), followed by an increase in the bunch number (much later), and finally an increase of the center of mass energy by a factor of 2.

Four particle physics experiments are currently being built at the LHC. The ATLAS detector is one of the two general purpose detectors, whose main physics goals are the search for the Higgs boson and the measurement of its mass, the search for supersymmetric extensions of the Standard Model, the physics of the top quarks, and the search for new particles like leptoquarks [2].

One of the most challenging aspects for ATLAS is the detection of muons with very high-precision momenta measurements. The ATLAS muon detector will be equipped with three layers of chambers in a magnetic field of 3–6 Tm bending power generated by a superconducting air-core magnet system [3]. The spectrometer is designed to provide a muon momentum resolution of better than 10% for transverse momenta up to 1 TeV/c over a pseudo-rapidity range of $|\eta| \leq 2.7$. This requires very accurate track sagitta measurement in the three layers of muon chambers and a high precision optical alignment monitoring system. Over most of the pseudo-rapidity range, measurements of the track sagitta are given by precision drift chambers, the Monitored Drift Tubes (MDT).

The ATLAS muon spectrometer uses a magnetic field which allows for the precise measurement of muon momenta. However, a consequence of this design is the absence of an iron absorber which could limit low-energy neutrons leaking out of the calorimeter and γ particles emitted from nuclei excited by the low energy neutrons. This leads to high background count rates in the muon chambers, especially in the forward region (Monte-Carlo simulations [4] predict background count rates of about 10 cm^{-2}s^{-1} in the barrel part and of up to 100 cm^{-2}s^{-1} in the end-caps).

The muon chambers are designed to cope with the expected background count rates at the LHC including an uncertainty factor (5). Nevertheless, for detectors any luminosity upgrade of the LHC beyond the design value is a big challenge for maintaining efficiency, resolution and operational reliability. At the S-LHC ten times higher count rates may be encountered if the background rate scales with the accelerator's luminosity. In this letter, we report on the development and test of drift tubes with high rate capabilities for the ATLAS MDT chambers.

II. The ATLAS MDT chambers at the LHC and beyond

The ATLAS MDT chambers consist of 2 triple or quadruple layers of drift tubes. The tubes are filled with an Argon and CO_2 gas mixture with a 93:7 ratio. The inner diameter of the tubes is 29.170 mm and a 50 μm gold-plated tungsten-rhenium is placed at the center. The aluminum tube wall is 0.4 mm thick. The tubes are operated at 3080 V, and they feature a 2 x 10^4 gas gain. The single tube resolution is better than 100 μm, resulting in a chamber position resolution of better than 40 μm.

Manuscript received November 16, 2007. This work was supported in part by the Swiss National Science Foundation Grant No. BS123456.

All Authors except F. R. are with the Max Planck Institute für Physik, München, Germany (corresponding author e-mail: federica.legger@mppmu.mpg.de).

F. R. is with Ludwig-Maximilians Universität of München, Germany.

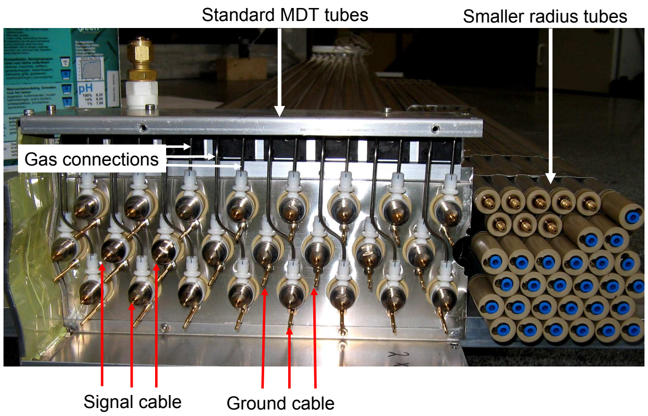

Fig. 1. A three-layer MDT chamber equipped with 30 mm diameter drift tubes. The gas, signal, and ground connections are shown. For comparison, 15 mm diameter drift tubes are piled up on the left.

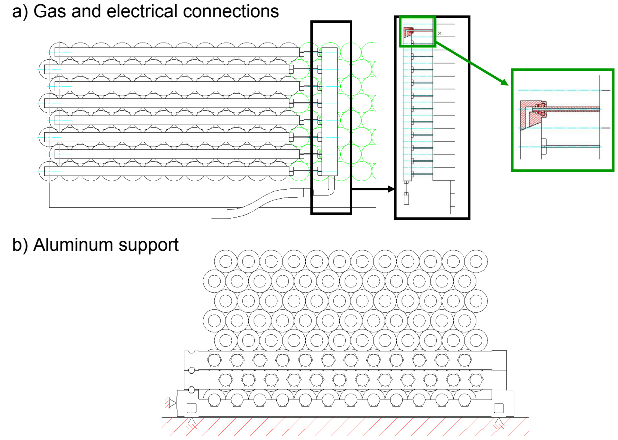

Fig. 2. Schematic drawing showing a 8-layer MDT chamber equipped with 15 mm diameter drift tubes.

The main background in the muon spectrometer is given by low energy neutrons and photons coming mainly from primary hadrons interacting with the ATLAS forward calorimeter, shielding, beam pipe and machine elements. The MDT chambers are known to suffer from the background countrates by a degradation of the spatial resolution due to space-charge fluctuations and by a degradation of the muon detection efficiency due to dead time effects leading to a loss of muon hits [5], [6]. At ten times the nominal LHC luminosity, the resolution degradation leads to a deterioration of the momentum resolution of the order of 50% while the efficiency may go down by 45%, which is a even more serious concern. At even higher background rates the occupancy of the chamber exceeds 50%. At this point efficient muon detection becomes impossible and new precision tracking detectors are needed.

III. Motivations for chamber design with smaller radius drift tubes

Converted γ particles usually create more than one hit in the read-out electronics. Therefore, in order to suppress hits due to secondary threshold crossings, the MDT front-end electronics currently uses a dead-time of 790 ns, which corresponds to the maximum drift time in an MDT tube. The maximum tube drift time is directly related to the occupancy of the tube, and defines therefore the tube operating limit. With the current design, the limit count rate is 700 kHz/tube, which results in occupancies larger than 50%. Lower occupancies can be obtained with smaller dead times.

The maximum tube drift time as a function of the drift tube radius has already been studied for the Ar:CO_2 gas mixture used in the current MDT chambers [7]. The space-time relationship shows that a maximum drift time of 200 ns can be obtained by halving the tube radius, leading to 30% lower occupancies than the current design. Owing to purely geometrical considerations, the smaller volume tubes leads to the reduction of occupancies by an additional factor 2. Adding up the two effects, one obtains 30% occupancy at a 1500 kHz/tube count rate. This leads to an efficiency loss of 25% with respect to the current design, which is acceptable.

The spatial resolution degradation due to space charge fluctuations is not a critical issue for drift radiuses smaller than 7 mm, due to the fast gas response in this region [5]. The gas gain drop is estimated to be around 15% at counting rates higher by an order of magnitude than that at LHC.

Additional advantages of the reduction of the tube diameter from its present value of 30 mm to 15 mm are: an 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; and a smaller background count rate per tube due to less conversions taking place in a smaller tube wall surface at the same background particle flux. Moreover, a more linear space-time relationship entices a lesser dependency on environmental parameters, such as temperature, magnetic field, gas pressure and background radiation, than in the current design.

IV. Design of chambers with smaller radius drift tubes

The approach followed in the realization of the first smaller radius tube prototypes profits of the experience gained in the design of the current MDT chambers. In the first design fase, our strategy implies therefore minimizing as much as possible the changes with respect to the current design. Thus the chosen baseline is the realization of drift tubes with 7.5 mm radius, with a 400 μm Al wall and a 50 μm tungsten-rhenium wire. In order to obtain the same electric field as in the current MDT tubes for distances from the wire smaller than 7.5 mm, the operating voltage is set to 2760 V. This allows us to use the standard ATLAS MDT readout electronics for the first tests.

One of the main issues of the design of a prototype chamber equipped with smaller radius drift tubes is the limited space available for electronics and gas connections (see Fig. 1). In Fig. 2, the handling of gas and electronics connections is shown for an 8-layer chamber. The wires are connected to the readout electronics and to the high voltage through short shielded cables. The aluminum support structure of the tubes is also shown.

At the tube ends, a cylindrical element called end-plug holds in position the wire (see Fig. 3). The end-plug deserves

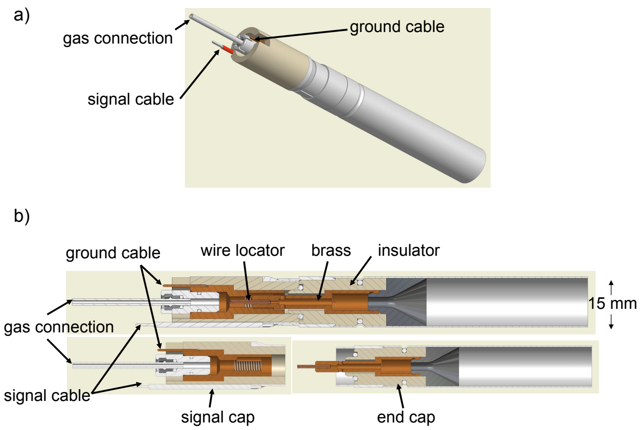

Fig. 3. End-plug design for 30 mm diameter drift tubes. a) 3-D schematic drawing of the end-plug. b) Longitudinal cut through the end-plug. The signal and end caps are also shown separately in the bottom drawing. The signal, ground and gas connections are shown.

careful design, since it must ensure the centricity of the wire with respect to the tube with an accuracy of 10 μm or better. Particular care must be paid to ensure the proper gas connectivity. As in the current MDT design, the central conductor holds the wire and serves for the gas transfer in and out of the tube. Brass is used for the electrical connections in the end-plug, and PEEK plastic is used as insulator. First high voltage tests show no leakage current for operating voltages up to 3500 V.

V. Cosmic-ray test stand with smaller radius drift tubes

As a first step in the development of smaller radius drift tubes for the ATLAS MDT chambers, a low-rate cosmic-ray test stand without magnetic field has been setup at the Max Planck Institut für Physik in München, Germany. The setup consists of a layer of 3 prototype drift tubes with 15 mm diameter, and a a triple layer of 8 standard MDT drift tubes with 30 mm diameter, who serve as reference detectors (see Fig. 4). Two layers of scintillation counters provide the trigger information for data readout. The distance between the small tube layer and the triple large tube layer is about 20 cm. Thus the precision of the tracking measurements that can be accomplished with this setup is limited by non-negligible multiple scattering phenomena.

The drift tubes are filled with an Ar:CO_2 (93:7) mixture operated at a pressure of 3 bar. The smaller tubes are operated at 2760 V, whereas the larger tubes are operated at 3080 V. The room temperature is monitored with external sensors on the tubes, and is kept constant at 20°C. Fluctuations are of the order of a few tenth of °C. Standard ATLAS MDT readout electronics is used for data acquisition.

The drift time spectrum of the 15 mm diameter tubes is shown in Fig. 5. The experimental curve is in excellent agreement with the simulated drift time spectrum obtained with GARFIELD, a program used to simulate drift chambers [8]. The drift time spectrum can be described with two modified

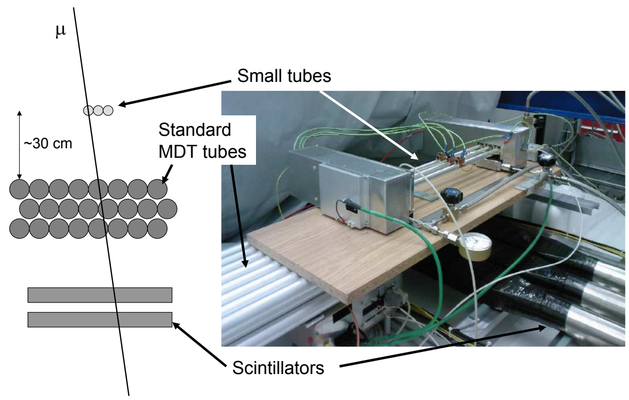

Fig. 4. Cosmic ray test stand realized at the Max Planck Institut für Physik in München.

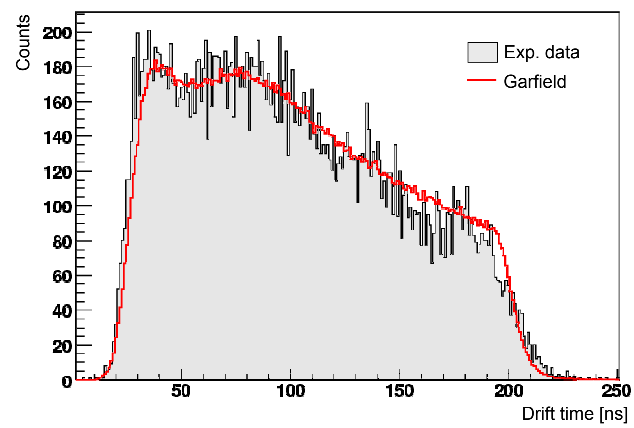

Fig. 5. Drift time spectrum of a 15 mm diameter drift tube. Cosmic ray data are shown in the solid histogram. The GARFIELD simulation is superimposed in red.

Fermi functions: $F(t) = \frac{A_0}{1+e^{-\frac{t-t_0}{T_0}}}$, for the rising part of the spectrum, which allows for the determination of the minimum drift time t_0, and $G(t) = \frac{s_1 e^{s_2 t}}{1+e^{-\frac{t-t_{max}}{T_{max}}}}$ for the falling part, which allows for the determination of the maximum drift time t_{max}. A_0, T_0, s_1, s_2 and T_{max} are also parameters to be determined by a fit. A fit of the measured drift time spectrum with the above defined functions $F(t)$ and $G(t)$ results in a measured maximum drift time of 180 ns, whereas a fit of the simulated spectrum gives a simulated drift time of 177 ns.

The measured space-time relationship for 15 mm diameter tubes is shown in Fig. 6. As expected, the gas response is sufficiently linear for drift radius smaller than 7.5 mm. The spread of the distribution is due to multiple scattering, however it is in qualitative agreement with the expectations from previous studies [7].

One of the prerequisites for excellent momentum resolution is a very high single tube efficiency (higher than 99% without background), which is defined as the probability of detection of a muon passing through a tube (with no requirement on the quality of the measurement of the drift radius). As one can see from Fig. 7, the measured single tube efficiency for 15 mm

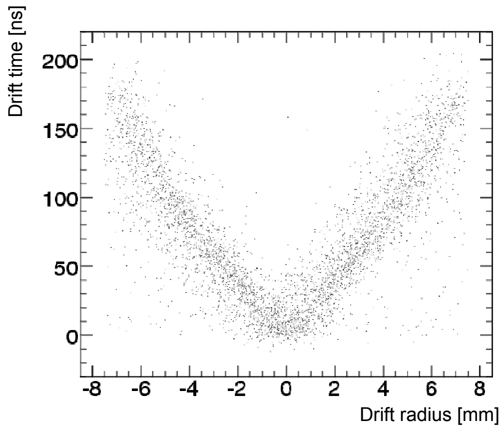

Fig. 6. Space-time relationship for 15 mm diameter drift tubes from cosmic ray data.

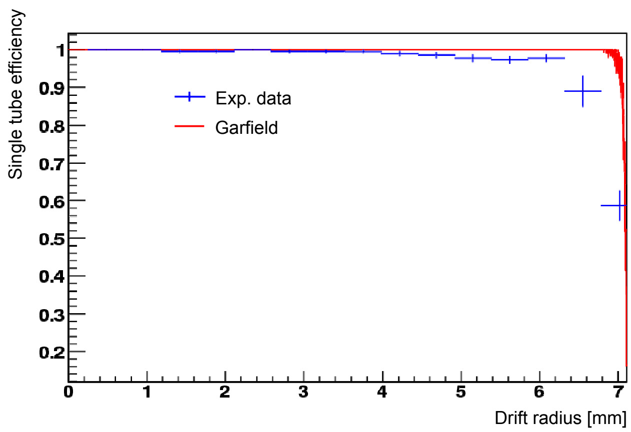

Fig. 7. Single tube efficiency as measured in cosmic ray tests (histogram with error bars). The GARFIELD simulation is superimposed in red.

diameter tubes is very close to 1. The discrepancy between cosmic-ray data and the simulation close to the tube wall is due to the above cited multiple scattering phenomena.

VI. Conclusion

A very harsh radiation environment at the S-LHC, the luminosity upgrade foreseen for the LHC, will force the replacement of the current ATLAS MDT chambers in the hottest part of the detector with a new technology that can withstand such particle fluxes. In this letter we propose the use of smaller radius drift tubes (7.5 mm vs. 15 mm as in the current design) for the MDT chambers at the S-LHC. We show that the two main problems that MDT chambers encounter at high counting rates, i.e. the efficiency loss due to high occupancy and the degradation of the spatial resolution due to space charge fluctuations, are not a critical issue with 15 mm diameter tubes. The new chambers will have a $\sim$10 times higher operating limit than the current design. We have tested first small tube prototypes in a low rate cosmic-ray test stand, and the experimental results are in excellent agreement with predictions from the simulation. Further tests are foreseen in the near future in an environment with high counting rates.

References

[1] ATLAS collaboration, *Workshop on ATLAS Upgrades for High Luminosity*, CERN 13-14 February 2005. Available: http://agenda.cern.ch/age?a045387.

[2] ATLAS collaboration, *ATLAS Technical Proposal*, CERN/LHCC 94-43, December 1994.

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

[4] S. Baranov *et al.*, *Estimation of Radiation Background, Impact on Detectors, Activation and Shielding Optimization in ATLAS*, ATLAS internal note, ATL-GEN-2005-001 (2005).

[5] M. Aleksa *et al.*, *Rate Effects in High-Resolution Drift Chambers, Nucl.* Instr. and Meth. A 446 (2000) 435-443.

[6] M. Deile *et al.*, *Performance of the ATLAS Precision Muon Chambers under LHC Operating Conditions*, Nucl. Instr. and Meth. A518 (2004) 65-68.

[7] M. Aleksa, *Performance of the ATLAS Muon Spectrometer*, Ph.D. Thesis, TU-Vienna/CERN, 1999.

[8] R. Veenhof, *GARFIELD: Simulation of gaseous detectors, Version 8.01, CERN*, write-up: http://wwwinfo.cern.ch/writeup/garfield.