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

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***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 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 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 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 may ultimately lead to an increase of the nominal LHC luminosity by an order of magnitude [1].

In the first phase, a stretching of the machine parameters up to their limits may lead to a luminosity increase of about a factor 2.3. Later luminosity upgrades foresee modifications of the interaction regions leading to stronger focussing, followed by an increase in the bunch number.

The ATLAS detector is one of the two general purpose detectors at the LHC, whose main physics goals are precision tests of the Standard Model of particle physics, the search for the Higgs boson and measurement of its mass, and the search for extensions of the Standard Model [2].

One of the most challenging aspects of the ATLAS experiment is the measurement of muon momenta with very high-precision. The ATLAS muon detector will be equipped with three layers of tracking 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 provided by precision drift tube detectors, the Monitored Drift Tube (MDT) chambers.

The ATLAS muon spectrometer has to withstand high radiation background mainly caused by low-energy neutrons leaking out of the calorimeter and γ particles emitted from nuclei excited by the low energy neutrons. At the LHC, Monte-Carlo simulations predict background counting 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 [4]. The muon chambers are designed to cope with the expected background count rates 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

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.

Low energy neutrons and photons coming from primary hadrons interacting with the ATLAS forward calorimeter, shielding, beam pipe and machine elements, are the main source of background in the muon spectrometer. The MDT chambers are known to suffer from high background counting rates 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

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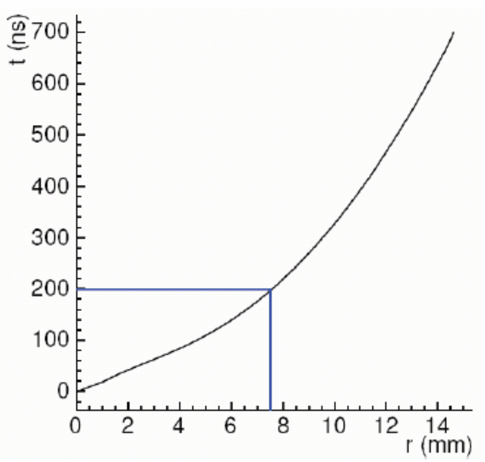

Fig. 1. Space-time relationship for the Ar:CO_2 gas mixture currently used in

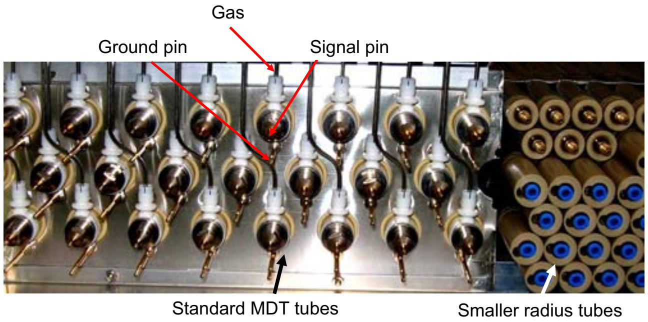

Fig. 2. A three-layer MDT chamber equipped with 30 mm diameter drift tubes. The gas, signal, and ground connections are shown. For comparison, 15 mm diameter drift tubes are piled up on the left.

may go down by 45%, which is a even more serious concern [7]. 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 SMALLER RADIUS DRIFT TUBES

The degradation of the muon detection efficiency at high background rates is due to the increased occupancy of the chambers. High rate tests show that tracking efficiencies higher than 80% can be obtained with the current MDT chambers for occupancies up to 30%, which corresponds to background rates lower than 450 kHz/tube. CITATION?

The occupancy of the tube is directly related to the maximum tube drift time, and defines the tube operating limit. The space-time relationship for the Ar:CO_2 gas mixture used in the MDT chambers (see Fig. 1) shows that a maximum drift time of 200 ns can be obtained by halving the tube radius, leading to occupancies lower by a factor 3.5 than the current design. Therefore drift tubes with 15 mm diameter are expected to have 30% occupancy at 1500 kHz/tube count rate.

ADD OLIVER SIMULATIONS?

TABLE I

COMPARISON BETWEEN VARIOUS PARAMETERS FOR 15 MM AND 30 MM DIAMETER DRIFT TUBES.

diameter	15 mm	30 mm
gas mixture	Ar:CO_2 (93:7)	Ar:CO_2 (93:7)
gas pressure	3 bar	3 bar
wire	50 μm W-Re	50 μm W-Re
tube wall	400 μm Al	400 μm Al
operating voltage	2760 V	3080 V
max. drift time	200 ns	700 ns
operating limit due to gain drop	5 kHz/cm^2	40 kHz/cm^2
occupancy at 1500 kHz/tube	30%	100%

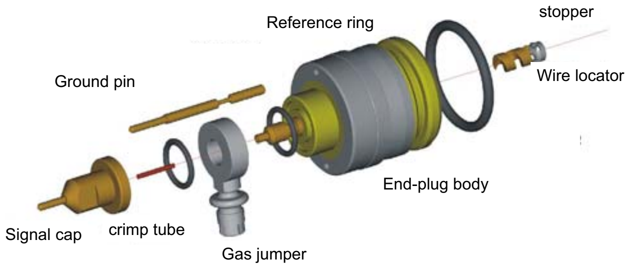

Fig. 3. End-plug design for 30 mm diameter drift tubes, currently used in the MDT ATLAS chambers.

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 due to space charge is about 15% at a count rate of 1 kHz/cm^2.

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The change in the operating voltage due to space charge is proportional to r^3, therefore 15 mm diameter drift tubes can withstand particle fluxes 8 times larger than the current MDT tubes.

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

In the first design phase, we aim to minimize as much as possible the changes with respect to the current design. Therefore 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

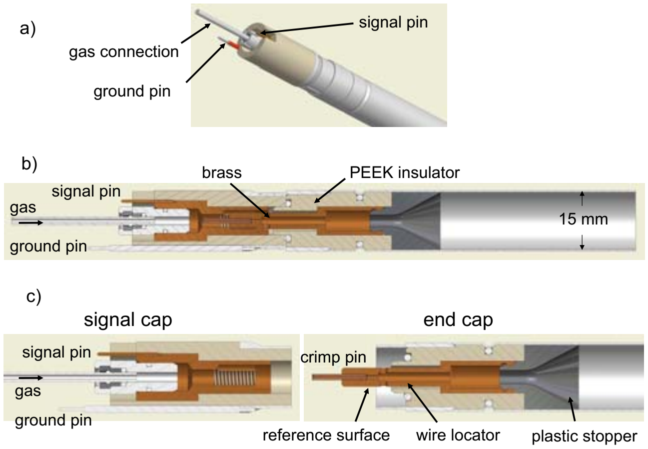

Fig. 4. End-plug design for 15 mm diameter drift tubes. a) 3-D schematic drawing of the end-plug. The signal, ground and gas connections are shown. b) Longitudinal cut through the end-plug. c) The signal and end caps are separately shown in the bottom drawing. The reference surface for chamber assembly, the wire locator, the plastic stopper and crimp pin are also shown.

readout electronics for the first tests. A summary of the various parameters used for 15 mm and 30 mm drift tubes can be found in Table I.

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. 2). The end-plug, a cylindrical element that holds in position the wire at the tube ends, has to be completely redesigned. The main features of the end-plug are: proper gas and electrical connections, centricity of the wire with respect to the tube, which must be ensured with an accuracy of 10 μm or better, and proper alignment of the tube with respect to the end-plug itself.

A schematic drawing of the end-plug currently in use in the MDT chambers can be found in Fig. 3, whereas the new design can be found in Fig. 4. In both cases, the central conductor holds the wire and serves for the gas transfer in and out of the tube. However, due to limited space, the gas distribution is co-axial in the new design, and not perpendicular to the tube as it is in the current MDT design.

The end-plug is composed by two elements: the signal cap, where the electronics and gas connections are located, and the end-cap, which is directly connected to the tube. The signal and ground pins are now connected from the signal cap to the readout electronics and to the high voltage through short shielded cables, whereas in the current design the electric connections are directly made to the signal-cap itself. First high voltage tests show no leakage current between the signal and the ground pin of the new end-plug for operating voltages up to 3500 V.

The centricity of the wire is ensured by a spiral element called wire locator, located in the end cap. The wire locator is held in place by a plastic element called stopper. is also used to ensure the appropriate gas tightness. In the new design, the plastic stopper In the signal cap, the wire is held by a crimp pin. During chamber assembly, a reference surface is used to properly align the tube. In the current design, the reference ring can be seen on the external end-cap surface. For space reasons, it is located on the conductive part inside the end-cap in the new design.

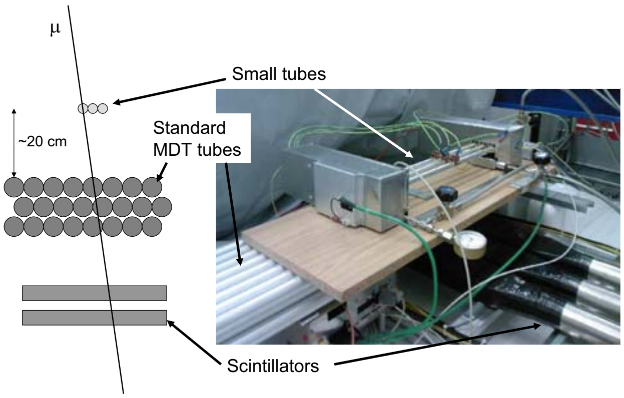

Fig. 5. Cosmic ray test stand realized at the Max Planck Institut für Physik in München.

V. COSMIC-RAY TEST STAND WITH SMALLER RADIUS DRIFT TUBES

A low-rate cosmic-ray test stand without magnetic field has been setup at the Max Planck Institut für Physik in München, Germany. Aim of these first tests are: the confirmation of the properties of the smaller radius drift tubes as expected from simulation, and the feasibility of the readout with the standard ATLAS MDT electronics.

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. 5). 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. 6. The experimental curve is in agreement with the simulated drift time spectrum obtained with GARFIELD, a program used to simulate drift chambers [9].

The measured space-time relationship for 15 mm diameter tubes is shown in Fig. 7. As expected, the gas response is linear for drift radius smaller than 7.5 mm, and qualitatively agrees with the expectations from previous studies [8]. The spread of the distribution is due to multiple scattering.

One of the prerequisites for excellent momentum resolution is a high (higher than 99% without background) single tube

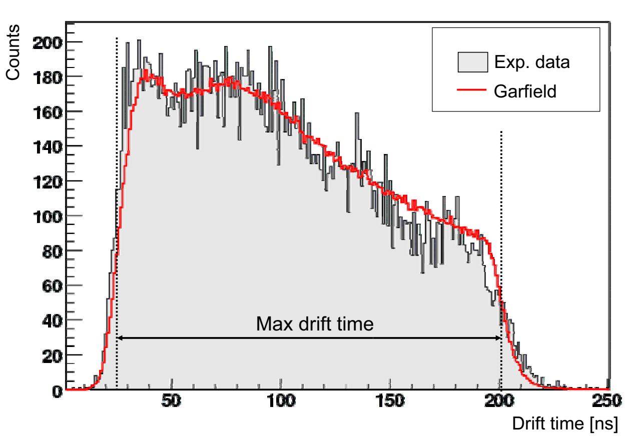

Fig. 6. Drift time spectrum of a 15 mm diameter drift tube. Cosmic ray data are shown in the solid histogram. The GARFIELD simulation is superimposed in red. The measured maximum drift time is 180 ns, and the simulated max drift time is 177 ns.

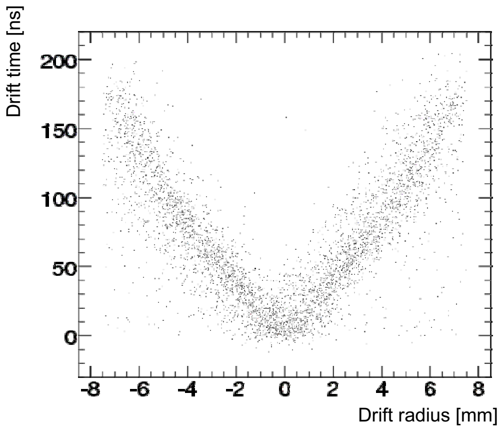

Fig. 7. Space-time relationship for 15 mm diameter drift tubes from cosmic ray data.

efficiency, 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. 8, the measured single tube efficiency for 15 mm 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 harsh radiation environment at the S-LHC, the luminosity upgrade foreseen for the LHC, will require the replacement of the current ATLAS MDT chambers in the hottest part of the detector with a new chamber type 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. 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, should not be a critical issue with 15 mm diameter tubes.

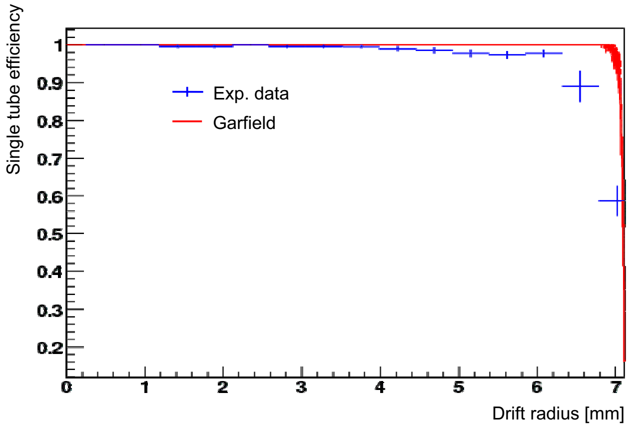

Fig. 8. Single tube efficiency as measured in cosmic ray tests (histogram with error bars). The GARFIELD simulation is superimposed in red.

The chambers equipped with 15 mm diameter drift tubes are expected to have a ∼10 times higher operating limit than the current design. We have tested first smaller radius drift tube prototypes in a low rate cosmic-ray test stand, and the experimental results are in agreement with predictions from the simulation. Further tests are planned in an environment with high counting rates, to confirm the chamber properties in the presence of radiation background.

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