Precision Drift-Tube Chambers for the ATLAS Muon Spectrometer at Super-LHC

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***Abstract*—The precise measurement of muon momenta up to 1 TeV/c is one of the most challenging aspects of the ATLAS experiment at the Large Hadron Collider (LHC) at CERN. The ATLAS muon spectrometer is equipped with three layers of Monitored Drift Tube (MDT) chambers in a magnetic field generated by a superconducting air-core magnet system which are designed to cope with neutron background counting rates of up to 500 cm^{-2}s^{-1}. However, 10 times higher background rates are to be expected at Super-LHC, the high-luminosity upgrade of the LHC. We investigate the possibility of increasing the rate capability of the drift tube detectors by reducing the tubes diameter from the current value of 30 mm to 15 mm. Cosmic ray test results of a prototype detector with 15 mm diameter drift tubes in the presence of γ ray fluxes of up to 2000 cm^{-2}s^{-1} are discussed.**

I. INTRODUCTION

IN the muon spectrometer of the ATLAS detector at the Large Hadron Collider (LHC) at CERN[1] large Monitored Drift-Tube (MDT) chambers are used for precision tracking in a toroidal magnetic field of superconducting air-core magnets. The MDT chambers are equipped with two triple or quadruple layers of pressurized aluminum drift tubes of 30 mm diameter and 0.4 mm wall thickness, filled with Ar:CO$_2$ (93:7) gas mixture at an absolute pressure of 3 bar. An operating voltage of 3080 V, corresponding to a gas gain of 2 x 10^4, is applied between the tube wall and the gold-plated 50 μm diameter tungsten-rhenium wire which is positioned at the center of the tube with an accuracy of 20 μm. The spatial resolution of individual drift tubes is 80 μm, which translates into a position resolution of 35 μm for a 6-layer chamber. This allows for a momentum resolution of better than for muon momenta of up to 1 TeV/c[2].

The ATLAS muon spectrometer will be exposed to high background fluxes of neutrons and γ rays with energies in the 1 MeV range, originating from interactions of the LHC collision products in the beam pipe, the shielding material, the calorimeters and accelerator elements. Detection efficiencies of the MDT chambers for these neutrons and photons are about 0.1% and 1%, respectively[3]. Monte Carlo simulations[4] predict the highest background rates in the ATLAS muon spectrometer in the inner layers of the endcap regions closest to the beam pipe. Due to uncertainties in the cross section and particle multiplicities in proton-proton collisions at a center-of-mass energy of $\sqrt{s} = 14$ TeV and limited knowledge of the showering processes in the shielding material and of the chamber sensitivities, a safety factor of 5 has been taken into account in the background rate estimates for the design of the ATLAS muon spectrometer. Hence, the MDT chambers are designed to cope with particle fluxes up to 500 cm^{-2}s^{-1} at the nominal LHC luminosity of 10^{34}cm^{2}s^{-1} which corresponds to a maximum counting rate per tube of 300 kHz in drift tubes of 2 m length.

The LHC upgrade schedule foresees a stepwise increase of the luminosity by up to an order of magnitude beyond the nominal value[5]. The background rates are expected to roughly scale with the luminosity. With luminosity increasing beyond the nominal value, muon chambers in the endcap regions of the ATLAS muon spectrometer will reach the limits of their rate capability. We investigate the possibility of using drift-tube chambers with reduced tube diameter up to the highest background rates expected at Super-LHC.

II. MDT CHAMBER PERFORMANCE AT HIGH COUNTING RATES

At high background rates, the MDT chambers are known to suffer from a degradation of the spatial resolution due to space-charge fluctuations[6], [7] and of the muon detection efficiency due to increased occupancy of the drift tubes[8]. At background rates beyond 2000 Hz/cm^2 the gas gain drop rapidly to 0 due to the large space charge density of ions created by the background hits. Both the problem of the efficiency drop and the gain drop can be overcome by reducing the tube diameter from 30 to 15 mm. The reduction of the tube diameter by a factor 2 reduces the gain drop by a factor $2^3 = 8$. Reducing the tube diameter from 30 to 15 mm while leaving all other parameters including the gas gain unchanged, leads to a reduction of the maximum drift time by a factor of ~ 3.5 from about 700 ns to 200 ns [9] and of the conversion rate of neutrons in the drift tube walls by a factor of two resulting in an occupancy reduction by a factor of about 7. In addition, the space-to-drift-time relationship becomes more linear reducing the sensitivity to space charge effects.

III. DESIGN OF 15 MM DIAMETER DRIFT TUBES

The design of the thin tubes with 15 mm diameter follows as much as possible the design og the current ATLAS monitored drift tubes with 30 mm diameter. The walls of the thins tubes

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are of 400 μm thick aluminium with a 50 μm tungsten-rhenium wire placed at the center of the tube. The thin drift tubes are filled with the same gas mixture Ar:CO$_2$ (93:7) at the same pressure of 3 bar as the ATLAS drift tubes. The operating voltage is set to 2730 V to obtain the same electric field in the thin tubes as in the ATLAS tubes for radii $<$7.5 mm. The gas gain is 20000. As a consequence of the similarities the standard ATLAS MDT electronics can be used for the read-out of the thin tubes. A summary of the operating parameters and characteristics of the thin tubs and the ATLAS drift tubes is given in Table I.

TABLE I
COMPARISON OF OPERATING 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	2730 V	3080 V
Max. drift time	200 ns	700 ns
Gas gain	20000	20000

IV. COSMIC-RAY TEST IN A HIGH RADIATION ENVIRONMENT

A detector prototype with thin drift tubes with 15 mm diameter was tested in a high radiation environment at the Gamma Irradiation Facility (GIF) at CERN in April 2008. The GIF is equipped with a 590 GBq ^{137}Cs source emitting 662 keV photons. The γ ray flux in the experimental area can be adjusted by means of lead filters of various thicknesses movable in front of the opening of the source [10].

The experimental set-up is depicted in Figure 1; a photography is shown in Figure 2. Two small MDT chambers consisting of two triple layers of 50 cm long ATLAS drift tubes at 31,5 cm distance were used for the reconstruction of cosmic muon tracks. A layer of 6 thin drift tubes of 15 mm diameter and 1 m length was placed between the reference chambers. 2 layers of scintillation counters (6 counters of 1.15 m length per layer) served as trigger for cosmic muons. The set-up was installed at a distance of about 1.50 m from the radioactive source. In order to keep accidental trigger coincidences low even at the highest background rates, the scintillation counters were shielded from the photon radiation by a 15 cm thick wall of lead bricks. The alignment of the thin tubes with the reference chambers was achieved by two spacers of hollow 30 mm diameter tubes holding the 6 prototype drift tubes in place between the two reference chambers. The length of the tubes of the reference chambers was set to 50 cm to keep the counting rates per tube within the operating limits of the ATLAS MDT chambers.

The thin drift tubes and reference chambers were read out with the standard ATLAS MDT electronics. The adjustable dead time of the read-out electronics was set to its minimum value of 200 ns.

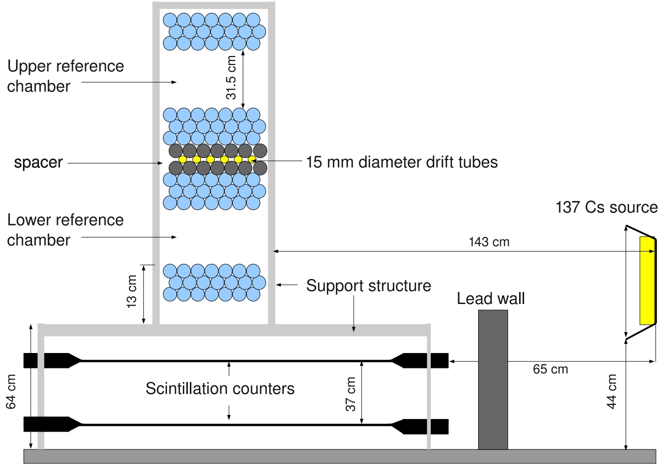

Fig. 1. Schematic drawing of the experimental set-up at the GIF.

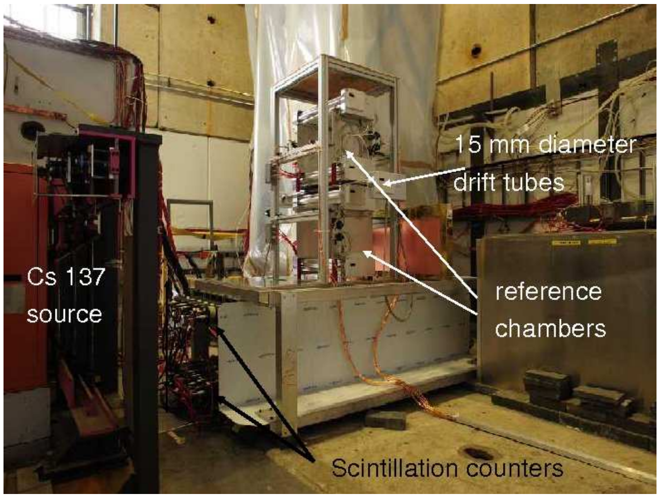

Fig. 2. The experimental set-up at the GIF. The lead wall had not been yet built at the time the picture was taken.

Measurements were made at different background counting rates depending on the choice of the filters. Apart from a reference run with the completely shielded radioactive source, background counting rates ranging from 90 to 330 kHz per thin tube corresponding to 600-2000 Hz/cm^2 were reached with different absorber settings. The counting rate decreases with increasing distance of the thin tube to the radioactive source. A 60% difference in the rates of the tube closest to the source and the tube with the largest distance is observed.

V. DRIFT PROPERTIES OF 15 MM DIAMETER TUBES

The cosmic muon tracks reconstructed in the reference chambers can be used to measured the relationship between the distance r of the reconstructed muon track from the anode wires of the thin tubes and the measured drift times t. Figure 3 shows a superposition of the r-t relationships measured at different background counting rates. The width of the r-t band is dominated by multiple scattering of the low momentum cosmic muon tracks in the chambers. The measured maximum drift time is in agreement with the expected value of 200 ns The r-t relationship is linear up to $r \approx 6$ mm where the drift velocity begins to drop. As the drift velocity is almost independent of r, it is also independent of the value of the electric field which falls off like $1/r$. The additional space charge in the thin tubes caused by background hits alters the electric field inside the tube, but it does not alter the drift velocity due to the insensitivity of the drift velocity to the electric field strength. The measured r-t relationships show the expected independence of the background counting rate.

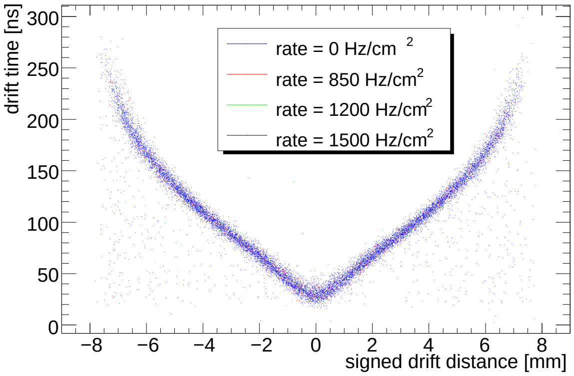

Fig. 3. Space-to-time relationship in 15 mm diameter tubes as a function of the counting rate. The sign of the drift distance indicates whether the anode wire was passed on its left or right.

VI. EFFICIENCIES OF 15 MM DIAMETER DRIFT TUBES AT HIGH RATES

Background hits can mask a muon hit when they hit a tube a dead time interval of 200 ns before the muon. These background hits have smaller drift times than the muon hits and the corresponding drift radii are smaller than the distance of the muon track from the anode wire of the tube. The muon detection efficiency of the tube is reduced.

The measured r-t relationships of the thin tubes can be used to measure the efficiency of the thin tubes to measure a muon hit with the correct radius. The residual distribution $r(t) - d$ where $r(t)$ denotes the drift radius measured by the small tube and d denote the distance of the reconstructed muon track from the anode wire of the small tube is Gaussian (see Figure 4).

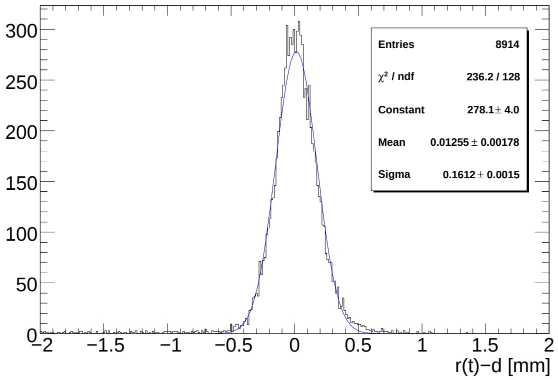

Fig. 4. Residual distribution at low counting rate.

Let σ be the standard deviation of the Gaussian function fitted to the residual distribution. The 3σ-efficiency of the small tube is defined as the fraction of traversing muon tracks for which

$$|r(t) - d| < 3\sigma.$$

The measured 3σ single-tube efficiency is plotted as function of the background counting rate in Figure 5. It is 95% without background radiation. It is lower than 100% because of δ electrons which are knocked out of the tube wall by the muons can mask muon hits when they traversed the tube at a smaller distance than the muons. The efficiency drops to about 90% at a counting rate of 300 kHz per thin tube.

Figure 5 also shows the 3σ single-tube efficiencies of the standard ATLAS drift tubes as measured in a previous run with a silicon tracking detector as external reference [11]. The measured efficiencies of the thin tubes are higher than the efficiencies achieved with the standard ATLAS drift tubes with the default dead time of 790 ns and the minimum dead time of 200 ns for first hits. The recovery of second hits at 200 ns for standard tubes with 200 ns dead time leads to the same efficiencies as for the small tubes at the same dead time. It should be noted, however, that the recovery of the second hits was easy with the silicon detector as external reference, but is far more difficult without it.

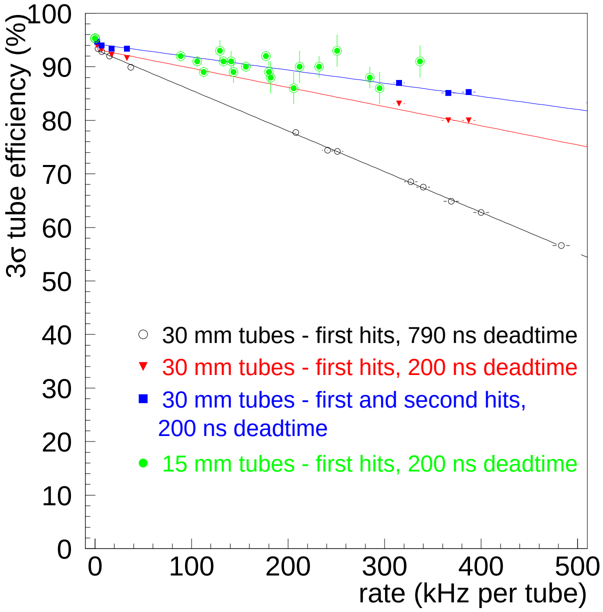

Fig. 5. 3σ single-tube efficiencies as function of the background rate. The green points show the measurements for the thin tubes. The efficiencies of the standard ATLAS drift tubes are taken from a previous measurement published in [11].

The background counting rate can increase to 3000 kHz per tube for the standard ATLAS drift tubes and to 1500 kHz for the thin tubes. Figure 6 shows the efficiencies of the ATLAS drift tubes extrapolated to rates expected at the Super-LHC. The efficiency drops to 0 already at 1250 kHz counting rate per tube when the electronics is operated with a dead time of 790 ns. Reducing the dead time to its minimum value of

200 ns increases the limit from 1250 kHz per tube to 2500 kHz per tube. At the maximum counting of 3000 kHz per tube a single tube efficiency of 20% can be reached with second-hit recovery. Thin drift tube are highly superior to the standard tubes. They have a 3 σ efficiency of 60% at the highest counting rate of 1500 kHz per tube at the Super-LHC and are promising candidates for a detector upgrade.

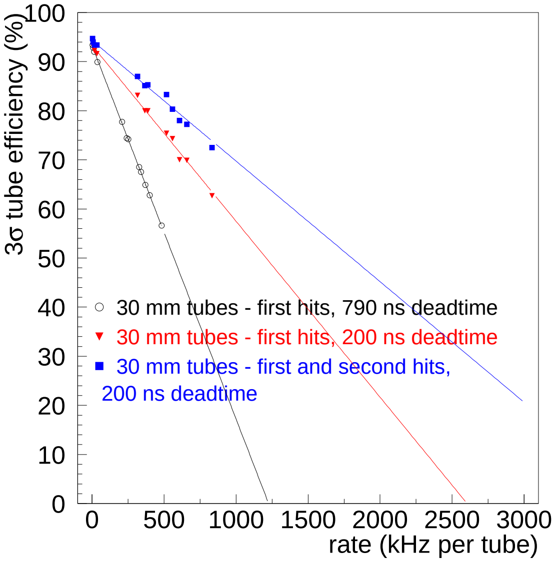

Fig. 6. 3σ single-tube efficiencies from [11] extrapolated to counting rates as expected for the Super-LHC. The additional efficiency decrease caused by the gain drop of the tubes is neglected in the extrapolation.

VII. CONCLUSIONS

The ATLAS MDT chambers are designed to withstand particle fluxes up to 500 $\text{cm}^{-2}\text{s}^{-1}$ and 300 kHz per tube. 10 times higher rates are expected at the planned Super-LHC providing 10 times higher luminosity than the LHC. ATLAS MDT chamber fail to operate a rate above 300 kHz and will have to be replaced by chambers with improved high-rate capability. Drift tube chambers with tubes of half the diameter of the present tubes provide the required high-rate capibility. First tests in the Gamma Irradiation Facility at CERN show that thin drift tubes show a small efficiency drop of 5% at counting rates of 300 kHz per tube. Extrapolation to the highest rates to be encountered at the Super-LHC give thin-tube efficiencies >60% which makes muon chambers with thin drift tube an option for an upgrade of the ATLAS muon spectrometer for the Super-LHC.

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