Performance of Drift-Tube Detectors at High Counting Rates for High-Luminosity LHC Upgrades

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Abstract

The performance of pressurized drift-tube detectors at very high background rates has been studied at the Gamma Irradiation Facility (GIF) at CERN and in an intense 20 MeV proton beam at the Munich Van-der-Graaf tandem accelerator for applications in large-area precision muon tracking at high-luminosity upgrades of the Large Hadron Collider (LHC). The ATLAS muon drift-tube (MDT) chambers with 30 mm tube diameter have been designed to cope with γ and neutron background flux of up to 500 Hz/cm^2. Background rates of up to 14 kHz/cm^2 are expected at LHC upgrades. The test results with standard MDT readout electronics show that the reduction of the drift-tube diameter to 15 mm, while leaving the operating parameters unchanged, vastly increases the rate capability well beyond the requirements. The development of new small-diameter muon drift-tube (sMDT) chambers for LHC upgrades is completed. Further improvements of tracking efficiency and spatial resolution at high counting rates will be achieved with upgraded readout electronics employing improved signal shaping for high counting rates.

Keywords: Drift tubes, MDT, sMDT, muon chambers, LHC, high luminosity, high counting rates

1. Introduction

The muon systems of the LHC experiments require high precision tracking detectors covering very large areas. Drift tube detectors provide a robust and efficient solution even at the high background rates of neutrons and γ rays experienced in the muon spectrometer of the ATLAS experiment which is equipped with muon drift-tube (MDT) chambers [1, 2] with 30 mm tube diameter. For the high-luminosity upgrades of the LHC, the background flux is expected to increase by almost an order of magnitude compared to the LHC design luminosity reaching a maximum of about 14 kHz/cm^2 in the forward regions of the ATLAS muon spectrometer. Besides requirements for higher selectivity of high momentum tracks and, therefore, improved momentum resolution at the first level of the muon trigger [3], muon tracking chambers with increased rate capability are needed in the high-radiation regions of the muon detectors. For the muon tracking chambers of the ATLAS experiment, which are operated in the field of superconducting air-core toroid magnets, a track segment resolution per chamber of better than 60 μm and, correspondingly, an anode wire positioning accuracy of better than 20 μm is required.

For these purposes, new small-diameter muon drift-tube (sMDT) chambers with 15 instead of 30 mm outer tube diameter have been developed. They are operated with the same sense wire diameter of 50 μm, the same gas mixture of Ar:CO_2 (93:7) at 3 bar absolute pressure, and the same nominal gas gain of G_0 = 20000 as the ATLAS MDT chambers. These parameters correspond to an operating voltage of 2730 V and a maximum drift time of 185 ns which is by about a factor of 3.8 shorter than for the 30 mm diameter as shown in Fig. 1. Together with the twice smaller tube cross section, this leads to 7.6 times smaller occupancy per unit tube length and to a vast improvement of the tracking efficiency and also of the spatial resolution at high rates.

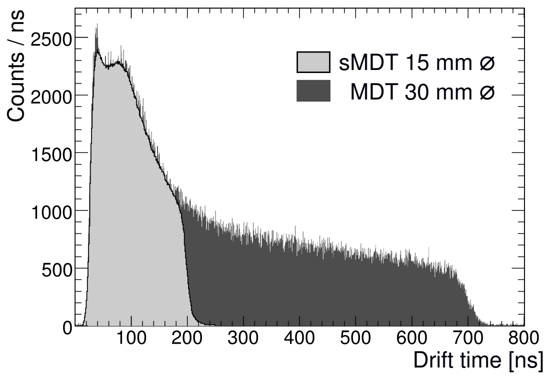

Figure 1: The measured drift time spectra of 30 and 15 mm diameter drift tubes with maximum drift times of about 700 ns and 185 ns, respectively.

2. sMDT chamber construction

A complete sMDT prototype chamber [4] has been constructed with 8 layers of up to 1 m long aluminum tubes of

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Figure 2: The sMDT prototype chamber of a size of one square meter.

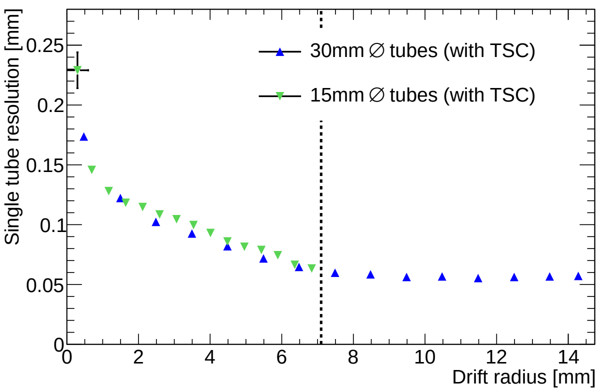

Figure 3: Measurement of the spatial resolution of 15 compared to 30 mm diameter drift tubes as a function of the drift radius r in high-energy muon beams at CERN without background irradiation. Time slewing corrections (TSC) have been applied using the pulse height information of the readout electronics. The resolution curves overlap in the common radial region as expected.

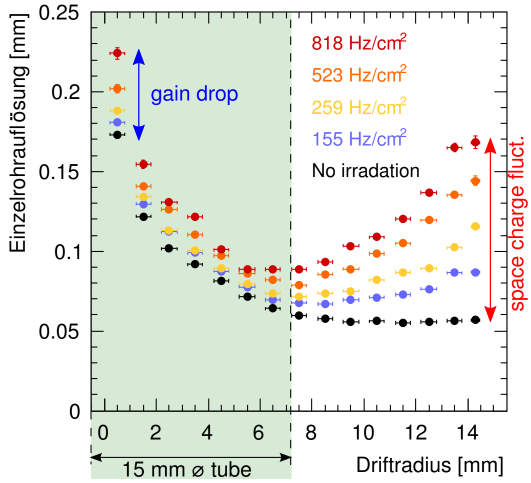

Figure 4: Spatial resolution of 30 mm diameter drift tubes as a function of the drift radius r measured for increasing γ flux at the CERN Gamma Irradiation facility [5].

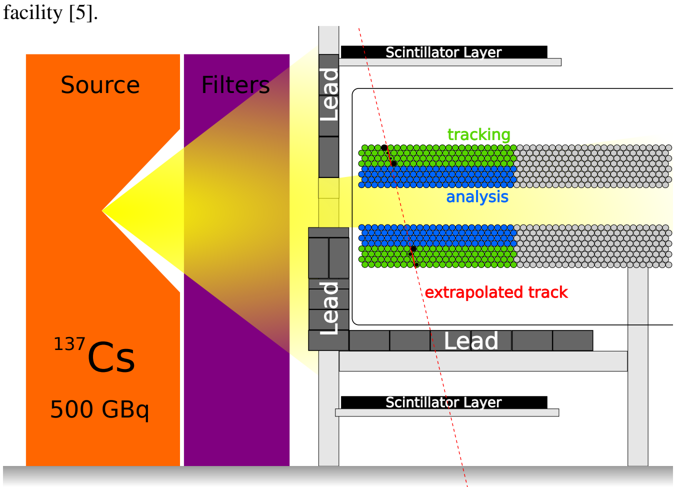

Figure 5: The test setup of the sMDT prototype chamber in the CERN Gamma Irradiation Facility. The unirradiated regions of the chamber serve as tracking reference for cosmic ray muons.

0.4 mm wall thickness mounted on either side of an aluminum space frame (see Fig. 2). Using precise mechanical jigging, each of the two multilayers of tubes has been assembled within one working day. The anode wire positions have been measured with a resolution of about 5 μm with cosmic ray tracks using two large MDT chambers with precisely known wire positions as tracking reference. The wire positioning accuracy has been measured to be better than 16 μm.

3. High-rate performance

The spatial resolution as a function of the drift radius of the 15 mm diameter drift tubes of the sMDT prototype chamber has been measured in the absence of background radiation in a high-energy muon beam at CERN (see Fig. 3). In the common radial range, it agrees very well with the resolution measured for 30 mm diameter MDT tubes under the same conditions [5]. Without background radiation, the spatial resolution averaged over the tube radius is worse for smaller-diameter tubes since the resolution improves with increasing drift distance. After time slewing corrections using the pulse height information provided by the readout electronics, the average resolution of 15 mm diameter tubes is 106 ± 2 μm compared to 83 ± 2 μm for the 30 mm diameter tubes [5].

With increasing flux of ionizing background radiation, the resolution deteriorates with increasing drift radius due to fluctuations in the space-charge density of the positive ions, and also at small radii due to the gas gain reduction caused by the shielding of the wire potential by the space charge. Fig. 4 shows that the effect of space charge fluctuations dominating for 30 mm diameter tubes in the radial range above 7.5 mm is strongly suppressed for 15 mm tube diameter. The gain loss at given primary ionisation from background radiation is to first approx-

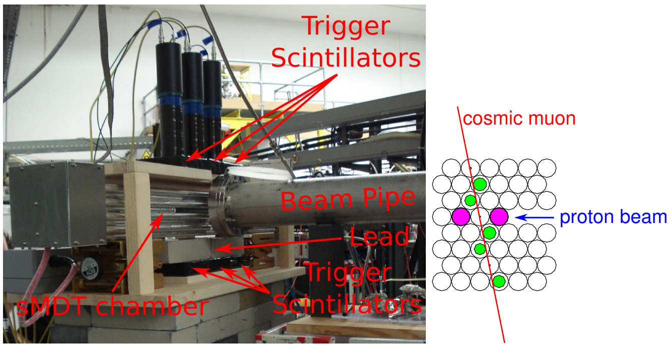

Figure 6: Test setup of a sMDT chamber in a 20 MeV proton beam delivered by the Munich Van-der-Graaf Tandem accelerator. The beam irradiates only the tubes of the middle layer (right, filled circles) over a longitudinal section of about 7 cm. The other tube layers serve as tracking reference for cosmic ray muons. The trigger segmentation along the tubes allows for the selection of muon tracks passing or missing the illuminated region.

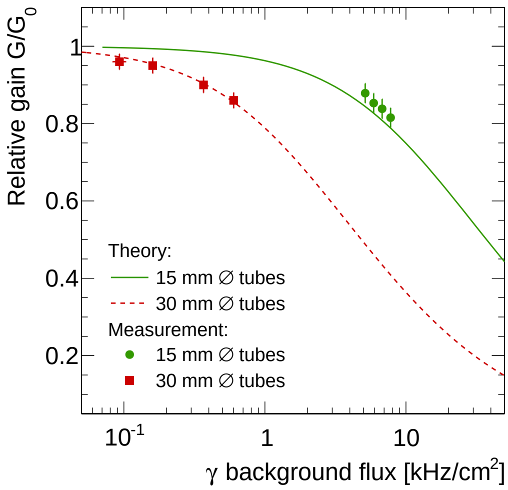

Figure 7: Measurements of the gas gain normalised to the nominal gain G_0 as a function of the γ background flux at GIF for 15 and 30 mm diameter drift tubes compared to predictions based on the Diethorn model [6] and taking into account with increasing background flux also saturation of the space charge production due to reduction of the electric field at the sense wire.

imation proportional to the inner tube radius to the third power and, therefore, is smaller by a factor of $(14.6\ mm/7.1\ mm)^3$ = 8.7 for 15 compared to 30 mm diameter tubes. The dependence of the gas gain on the γ background flux from a 500 GBq ^{137}Cs source has been measured for 30 and 15 mm diameter tubes in the Gamma Irradiation Facility at CERN using the pulse height information of the readout electronics (see Fig. 7). It is well described by models obtained by iterating the Diethorn prediction [6] for the gas gain as a function of the electric field at the sense wire with the space charge production in this field and shows the expected suppression of the gain loss in 15 mm diameter tubes.

The relevant quantity for evaluating the chamber tracking efficiency and resolution in the presence of background is the so called 3σ single-tube efficiency which is defined as the probability of a muon hit in a drift tube to lie on the reconstructed muon track within three times the drift tube resolution σ. Background signals may mask subsequent muon hits for the duration of the signal pulse length and the electronics deadtime leading to a decrease of the 3σ efficiency with increasing background counting rate. The standard ATLAS MDT readout electronics [7] used in all performance tests allows for an adjustment of the deadtime between a minimum value of 175 ns and the maximum of 790 ns which is used for the ATLAS MDT chambers in order to suppress secondary hits from late arriving ionization clusters. With the minimum deadtime setting which is applicable for the much shorter drift times of the sMDT tubes, the degradation rate of the 3σ efficiency is expected to improve by about a factor of 9 compared to 30 mm diameter tubes where a factor of 2 is due to the twice smaller tube cross section exposed to the radiation.

The high-rate performance of the sMDT chambers equipped with standard MDT readout electronics has been studied with cosmic ray tracks in the Gamma Irradiation Facility (GIF) at CERN (see Fig. 5) at γ fluxes of up to 8.5 kHz/cm^2 corresponding to counting rates of up to 1200 kHz/tube and in a 20 MeV proton beam at the Munich Van-der-Graaf Tandem accelerator (see Fig. 6) at counting rates of up to 1400 kHz/tube. In contrast to the uniform illumination of the tubes at GIF, the proton irradiation is localised to a 7 cm wide longitudinal section of one tube. The trigger segmentation allows for the selection of muon tracks traversing either the irradiated or the unirradiated regions of the tube for the measurements of the resolution depending on the space charge and of the efficiency depending on the counting rate, respectively. Equivalent γ fluxes corresponding to the proton rates have been determined using the 15 mm diameter gain curve in Fig. 7 and measurements of the gas gain (see above) under proton irradiation. The results for the average spatial resolution and the 3σ tracking efficiency in Figs. 8 and 9 show vast improvements from 30 to 15 mm tube diameter tubes increasing with the background rate. The 3σ efficiency measurements at GIF contain also hit efficiency loss due to gain loss which is, however, negligible at the γ rates reached at GIF.

With increasing counting rates, effects of the pile-up of muon signals on preceding background pulses deteriorate the resolution and efficiency of the 15 mm diameter tubes operated with short deadtime (see Fig. 10). If a minimum time separation between successive hits of 600 ns is required (pile-up veto), the measured spatial resolution is considerably improved and agrees very well with the expectation from the 30 mm diameter tube measurements with maximum deadtime and no pile-up effects observed (see Figs. 8 and 9)) which is derived by averaging the data points in Fig. 4 only up to a radius of 7.1 mm and scaling the γ flux with the gain ratio of 8.7. The 3σ efficiency of the 15 mm diameter tubes can also be considerably improved by suppressing the pile-up effect (see Fig. 9). The pile-up effects will be eliminated in an upgraded version of the readout electronics which is under development by employing active baseline restoration.

From the results in Figs. 8 and 9, one derives a spatial resolution of better than 40 μm and a tracking efficiency of better than 99% for 2 times 6 layer sMDT chambers at the maximum background rates expected in the ATLAS muon spectrometer at high-luminosity LHC.

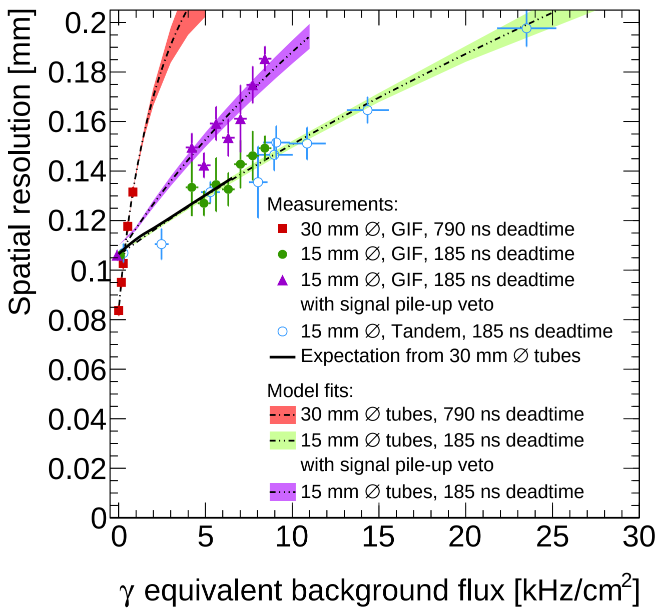

Figure 8: Average spatial resolution of 15 mm diameter drift tubes with and without electronic signal pile-up effect under γ (GIF) and proton (Tandem) irradiation as a function of the equivalent γ flux (see text) compared to the results for 30 mm diameter tubes. The maximum background rate expected in the ATLAS muon detector at high-luminosity LHC is 14 kHz/cm^2.

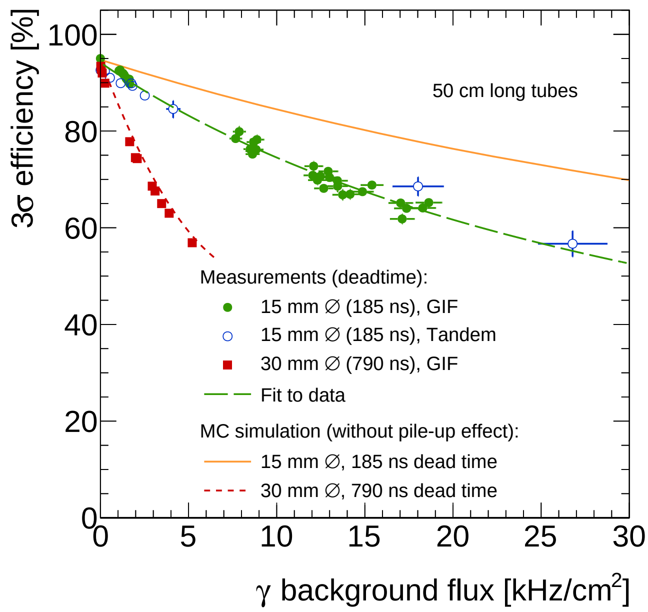

Figure 9: Dependence of the 3σ tracking efficiency of 15 mm diameter drift tubes on the background counting rate expressed in terms of the corresponding γ flux in 0.5 m long tubes compared to the results for 30 mm diameter tubes and to the expectation without electronic signal pile-up effect. Without background irradiation the 3σ efficiency is 94% due to δ-rays created by muon interactions in the tube walls which produce signals earlier than the muons. The maximum background rate expected in the ATLAS muon spectrometer at high-luminosity LHC is 14 kHz/cm^2.

4. Ageing tests

Ar:CO_2 gas and only materials already certified for the ATLAS MDT chambers are used for the sMDT drift tubes in order to prevent ageing. No ageing has been observed in MDT tubes up to a charge of 0.6 C/cm collected on the anode wire [1]. The sMDT tubes [4] have been irradiated with a 200 MBq $^{9}0$ Sr source over a period of 6 months accumulating an integrated charge of 6 C/cm on the wire still without sign of ageing.

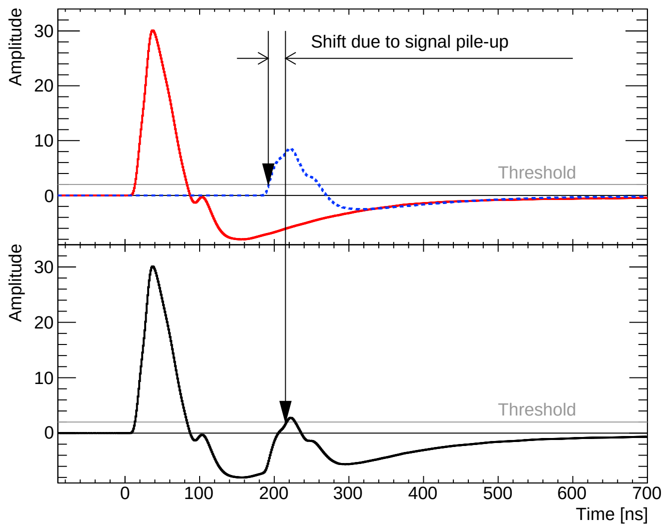

Figure 10: Illustration of the signal pile-up effects present for the standard MDT readout electronics with bipolar shaping and minimum deadtime setting used for the 15 mm diameter drift tubes. The large undershoots due to large γ and neutron signals may lead to the loss of subsequent muon hits and will, in general, cause additional time slewing.

5. Conclusions

The development of fast high-precision muon drift-tube detectors (sMDT chambers) for high-luminosity LHC upgrades is completed. The high-rate performance of the new chambers exceeds the requirements for operation at the highest background rates at high-luminosity LHC upgrades. Several sMDT chambers are under construction for the upgrade of the ATLAS muon spectrometer in the 2013/14 LHC shutdown period. A smaller sMDT chamber has already been operated in the highest irradiation region of the ATLAS muon spectrometer during 2012 data taking confirming the expected performance.

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