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Long-term irradiation study of sMDT drift tubes with an integrated accumulated charge of 60 C per wire using beta-electrons from a ^{90}Sr source

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ABSTRACT

Two ATLAS sMDT drift tubes have been irradiated for almost 1 year using a ^{90}Sr beta-decay source. An integrated charge of 62 C has been accumulated on each of both anode wires over an anode-wire region of about 7.5 cm. Taking into account the intensity distribution of the irradiation corresponds to a maximum accumulated line charge density of about 14 C/cm. At the innermost position of the ATLAS forward muon spectrometer 10 C/cm are expected for 10 years of high-luminosity LHC operation and for this detector type at gas gain 20000. To investigate potential outgassing, the endplug region of the drift-tubes, where no gas amplification occurs, was irradiated additionally using about half the beta-electrons emitted from the source. The other beta-electrons were irradiating an active part of the gas volume for monitoring purpose. During four months the endplugs were irradiated by 5 C/cm equivalent. All observed anode currents were very stable over the whole period of irradiation and thus no sign of deterioration in the performance of both drift tubes was observed. This indicates that no ageing effects occurred and that no performance loss due to outgassing of any plastic surfaces has been observed. All components that have potential contact to the detector gas Ar:CO_2 with a mixture of 93:7 (percent volume) have been carefully and properly chosen. The required cleanliness of all tube- and gas components has been achieved during construction and operation of these drift tubes.

1. Introduction

The new generation of ATLAS MDT drift tube chambers, the so called sMDT chambers (small diameter muon drift tube chambers), consists of drift tubes with a diameter of 15 mm, i.e. the diameter has been reduced by a factor of 2 in regard to the D = 30 mm of the legacy MDT (monitored drift tube) chambers used in the muon spectrometer since the beginning of ATLAS. The new chambers can deal with highly increased background rates, as the occupancy is reduced by more than an order of magnitude and as the sensitivity to space charge effects scales with at least the third power of the radius [1,2]. Further advantages are: more tube layers can be integrated into a multilayer in the same chamber volume with considerably improved track reconstruction efficiency and the relation between position and drift time becomes almost linear, a fact that eases considerably the analysis of muon tracks in the ATLAS experiment [1,2]. For these reasons the small diameter muon drift tube chambers have been taken into account as precision tracker for the ATLAS new Small Wheel (NSW) in 2012, as replacement for the 30 mm drift tube chambers but also as replacement for the CSC chambers (cathode strip chambers) sitting closest to the LHC (Large Hadron Collider) beamline and experiencing thus the largest background intensity. For the innermost part of the NSWs, where the highest background rates are expected within the muon spectrometer, recent measurements at luminosities of 2×10^{34} cm^{-2} s^{-1} are predicting background induced rates close to 25 kHz/cm^2 [3] at HL-LHC conditions (high-luminosity LHC: 7.5×10^{34} cm^{-2} s^{-1}) for the time after 2029. In this context it was decided to start a new long-term stability irradiation study for sMDT drift tubes using a ^{90}Sr beta-decay source with the goal to acquire amounts of charges beyond 10 C/cm thus exceeding considerably the irradiation level expected at HL-LHC over 10 years. Meanwhile both NSWs are installed in the ATLAS forward muon spectrometer. Micromegas (micro mesh gaseous structure) and sTGC (small strip thin gap chamber) detectors have been chosen finally as detector technology. Instead sMDTs are considered as new BIS78 MDT chambers (ATLAS Barrel Inner Small chambers sitting close to the endcap part of the muon spectrometer) and they will replace in the Phase-II upgrade the BIS MDT chambers (Barrel Inner Small) in the ATLAS muon spectrometer. This ageing study proves convincingly that the new BIS and the BIS78 sMDT chambers, that experience a factor 10 to 25 smaller background levels than the inner part of the NSWs, will work over the complete lifetime of ATLAS without any problem and with excellent performance.

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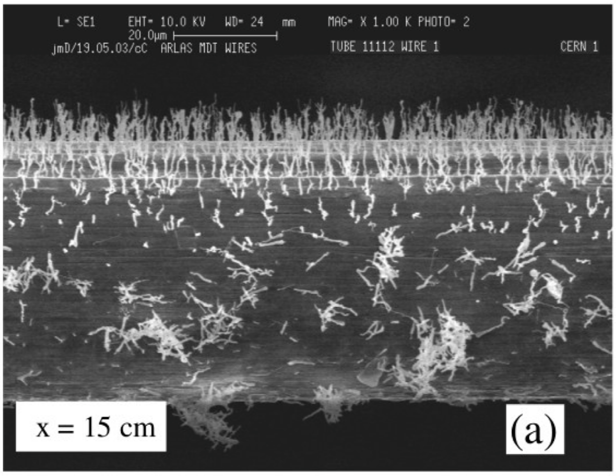

Fig. 1. About 20 years ago, the built-up of whiskers and other structures around the anode wire of a 30 mm ATLAS MDT drift tube was observed during irradiation when the gas system was polluted by silicone grease. A steady decrease of the anode current was observed hereby. The grease was contained in a valve that was used before in a different experiment at Cern. Without the silicone pollutant the drift tubes show no ageing using Ar:CO2 gas mixtures.
Source: Fig. taken from [4].

It is well known that drift tube detectors using Ar:CO_2 gas mixtures in combination with certified and properly cleaned materials are not subject to ageing. Only when, as in Fig. 1, the gas system or detector components are polluted by silicone or other ageing inducing contaminations a deterioration of the detector performance as function of time is observed. This is usually accompanied by a change - often a steady decrease - of the anode current. Therefore it is important to test a new detector technology for ageing phenomena. Particular care must be applied to avoid pollution of any material and to use well certified materials only.

The basic idea of this study is as follows: the current on the anode wires of the two drift tubes is directly proportional to the gas gain and is expected to be constant at constant irradiation. Ageing effects, as in [4], induce usually a steady decrease in gas amplification and thus in anode current. In rare cases an increase in anode current might be observed. The non-observation of a change in current over a long period of time is therefore an indication for non-occurrence of ageing effects. The gas amplification is according to Diethorn's [4] representation of the Townsend theory density dependent and thus temperature and pressure dependent. The gas in the tubes is well pressure stabilized to 3 bar but the tubes were subject to small temperature variations over the year. Tentative linear temperature correction to one of the data sets decreased the variation in anode current impressively to the percent level, indicating no observed ageing effects at all.

2. Tube construction

Fig. 2 shows a schematic of an sMDT tube. A 15 mm diameter aluminum precision tube with 0.4 mm wall thickness serves as cathode body. The tube is industrially cleaned and alodyned on the inside and outside using Surtec 650, an environmentally permitted surface coating that prevents corrosion of the surfaces and that maintains excellent long-term conductivity of the surfaces. The procedure of the Surtec coating degreases and removes all remnants from the tube production. All other conductive parts are gold plated. As insulator material and for the gas distribution PBTP (polybutylenterephtalat) was chosen, a material that is known to not form cracks after injection molding. The molded PBTP parts showed no sign of outgassing in gas chromatography mass spectrometry. PBTP was used already in the gas distribution system of the legacy MDT detectors at ATLAS and is thus established. EPDM o-rings (Ethylen-Propylen-Diene-Monomer rubber) are used to provide gas tightness. The holding and threading system for the 50 μm gold plated tungsten wire is made from brass. A copper tube is used to crimp the wire and keep its tension at 350 g. All parts are cleaned very carefully before assembly. The o-rings are washed by ethanol using a professional tumbler and are absolutely free of grease or silicone oil remnants. All other parts are cleaned using ethanol as well. The cleaning procedure has been developed for the legacy MDT tubes and has proven to be safe.

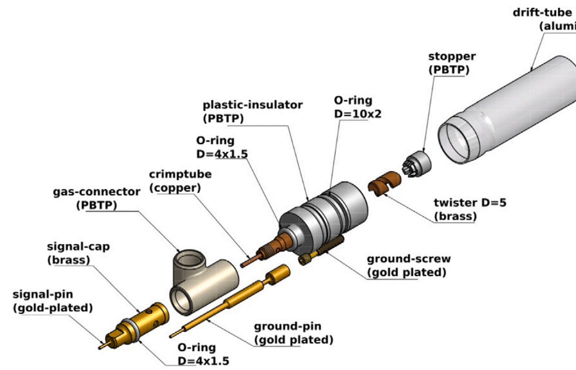

Fig. 2. Schematic drawing of an sMDT tube [2]. A 15 mm diameter aluminum precision tube with 0.4 mm wall thickness serves as cathode body. A 50 μm gold plated tungsten wire serves as anode. The anode voltage is applied to the gold-plated signal pin. Each tube is connected via a gold-plated ground-pin to the electrical ground potential. PBTP was chosen as insulator material and for gas distribution. EPDM o-rings provide gas tightness. The holding and wire-threading parts are made of brass.

3. Experimental setup

Fig. 3 shows a photograph of the experimental setup and Fig. 4 adds details in side and top view. A 213 MBq ^{90}Sr source emits beta-electrons with an endpoint energy of 546 keV from the ^{90}Sr to ^{90}Y beta-decay and with an endpoint energy of 2.282 MeV from the subsequent ^{90}Y to ^{90}Zr beta-decay. A large part of these beta-electrons loses an energy of about 180 keV in the 0.4 mm aluminum wall of the sMDT tubes and about 9 keV in 15 mm of the detector gas Ar:CO_2 93:7 (percent volume) at 3 bar. Beta-electrons below 0.3 MeV stop within the 0.4 mm thick tube wall. The ^{90}Sr source has the shape of a 10 mm long needle of 2 mm diameter. Only the uppermost 2 mm contain the active ^{90}Sr material. Beta-electrons emitted under an angle larger than 55 degrees are absorbed in the PMMA (plexiglass) holding vessel.

It is important to use a light material for the source holder to minimize photons created by bremsstrahlung. The tubes are sMDT tubes from serial production, the gas system is made from purified stainless steel tubing with two short pieces of polyethylene tubing for insulation of the high voltage applied to the anode wires. Only well cleaned stainless steel valves were used in the gas system similar to the gas system for the legacy muon MDT detectors in ATLAS. The tubes were operated under standard conditions for muon (minimum ionizing particle) detection at ATLAS. This corresponds to a gas gain of 20 000 at an anode voltage of 2.73 kV, a pressure of 3 bar and a gas flux of few volume exchanges per day. The purpose of the PMMA source holder is two-fold: it is supposed to limit the emittance of the beta-irradiation to an angle of 55 degrees, all other beta-electrons are stopped in the PMMA material, and it allows to handle the strong source without danger and with high degree of reproducibility of the relative position to the tubes. For the irradiation period January - July 2012 the source was sitting at about the position shown in Fig. 3. Later the source was moved by about 5 cm against the endplug of the tube to study the influence of the irradiation of the endplugs.

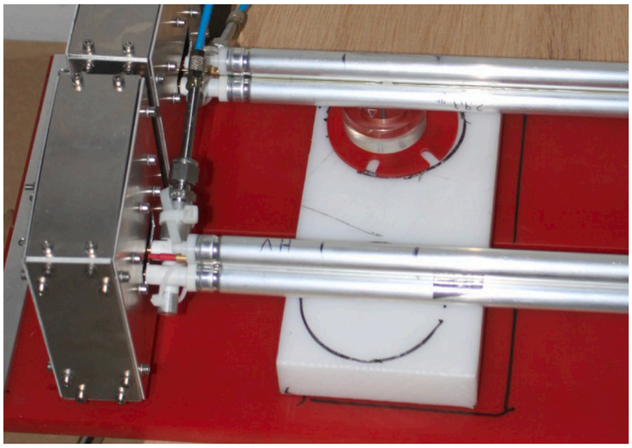

Fig. 3. Experimental setup for the irradiation of two sMDT drift tubes. The two tubes in the top part of the figure have been irradiated for about one year using a 213 MBq 90Sr source placed in the center of the PMMA (plexiglass) shielding vessel. Both tubes in the lower part of the figure have been irradiated for a short time only and they were removed later. During this irradiation the source was placed in between the four tubes creating half the current per anode only. This pretty ineffective irradiation was stopped after short time and the setup was changed to the two-tube irradiation described before.

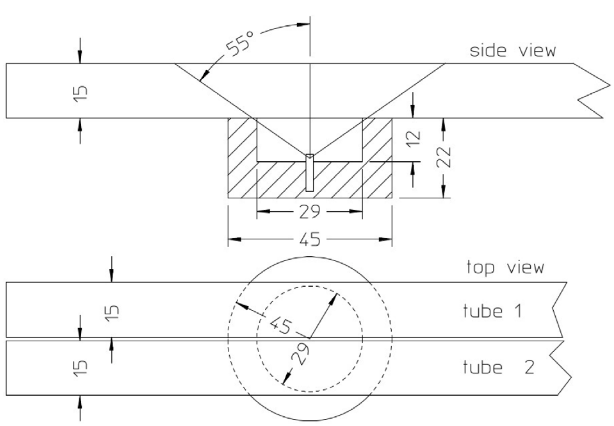

Fig. 4. Detail of the PMMA source holder (shaded). The ^{90}Sr 10 mm long needle source of diameter 2 mm is sitting in an 8 mm deep 2 mm hole in the bottom of the holder. Only the beta-electrons emitted within an angle of 55 degrees enter the tubes and are not absorbed in the PMMA material. The active part of the source is sticking out of the PMMA. It has in reality a size of $2 \times 2\,\text{mm}^2$. For simplicity, the source is approximated in the following as a point source being in z separated by 11 mm from the tubes.

4. Measurements

Fig. 5 shows the currents on the anode wires in the two irradiated tubes (blue: tube 1, red: tube 2) from August 2011 until July 2012. From January 2012 on the irradiation is most intense with anode currents around 3 μA. A charge of about 39 C was accumulated during this period in the active volume of the tube, see Table 1. The constant anode currents in the figure indicate that no deterioration of the performance of the tubes was observed. During all measurements the temperature on the surface of the tubes, the pressure and the gas flux were monitored.

The gas system was run all time in pressure stabilized mode at a pressure of 3 bar. The small fluctuations in current seen in Fig. 5 follow predominantly the variation of the temperature. We observed an almost linear dependence of anode currents and temperature, as indicated in Fig. 5, where the currents are varying proportional to the fluctuations of temperature. Linear temperature correction has been performed tentatively on the blue current distribution from Fig. 5. The corrected

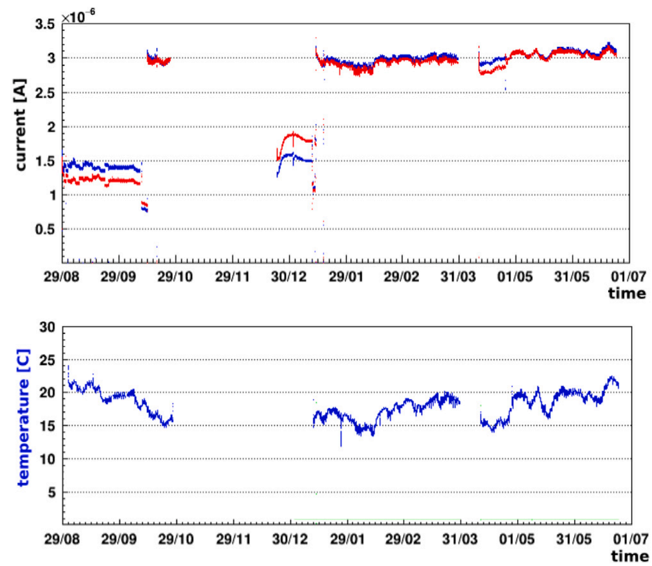

Fig. 5. Anode currents during the first and second part of the irradiation of two sMDT tubes from August 2011 to July 2012 (blue data points: tube 1, red data points: tube 2). In the first two months the irradiation intensity was reduced by about a factor of 2 as four tubes were irradiated, see Fig. 3. Later only 2 tubes were irradiated with the source sitting considerably closer to the tubes. Thus the irradiation intensity could be increased by a factor of 2. During the downtime October - December 2011 the irradiation was interrupted due to organizational issues and the christmas break. The fluctuations in the current distributions follow the environmental temperature variations shown in the bottom part of the figure.

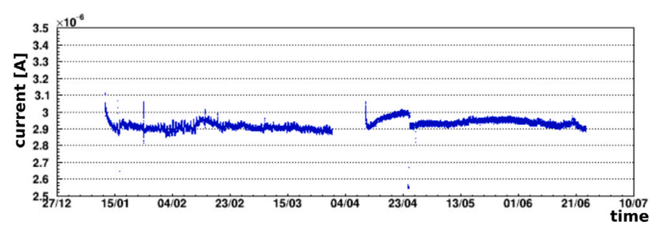

Fig. 6. Temperature corrected current 1 (blue) from Fig. 5. The variations in current are reduced impressively to the percent level using linear temperature correction.

data are shown in Fig. 6 for the period Jan. - July 2012. The variations are much smaller than in the uncorrected current distribution. Not all details could be fully compensated as e.g. periods where the tube was not in thermal equilibrium. In Fig. 6, the small fluctuations on the percent level only – please take into account the expanded Y-scale – are supporting even more that no indication of tube-deterioration is visible.

Fig. 7 shows the anode currents of the two irradiated tubes during the measurement period in 2013. Here the emphasis was to irradiate also the endplug of the drift tube, as required by the ATLAS collaboration and to search for harmfull irradiation induced outgassing. For this the source was moved closer to the endplug. A bit more than half of the distribution of the beta-electrons that formerly irradiated the active volume are now, as the source was shifted against the endplug, stopped in the material of the endplug and they do no longer create a signal in the active volume of the tube. Only those beta-electrons that are emitted in direction of the active gas volume contribute still to the signal in the gas. As a consequence the currents in both tubes are reduced to about 1.3 μA. As the distribution and the intensity of the beta-electrons is solely given by the source and the geometry of the PMMA source holder, and as only the PMMA vessel has been shifted, we assume that the missing part of the current on the anode wire is irradiating the endplugs. The interaction of those beta-electrons that stopped in

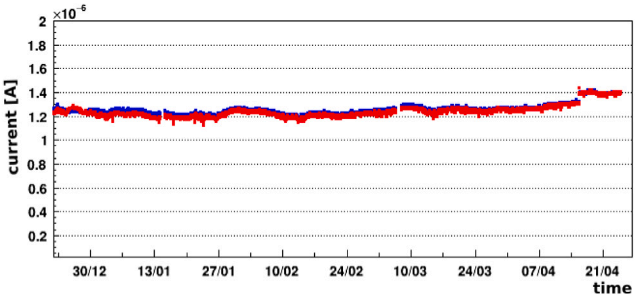

Fig. 7. Currents (blue: tube 1, red: tube 2) during the third part of the irradiation of two sMDT tubes from end of 2012 to April 2013. The intensity of the anode current is reduced from 3 to 1.3 μA as a large part of the beta-electrons is stopped in the endplug of the tube. In the endplug regions no charges are produced in the active volume by the beta-electrons. The non-observation of loss in detector performance due to irradiation induced outgassing is a positive result. About 5 C/cm active area equivalent line charge density was accumulated on each of the two endplugs.

Table 1
Currents, accumulated charges, and maximum accumulated line charge density during three periods of irradiation. During the first two periods only active tube volume was irradiated, during the third period also a substantial part of two endplugs was irradiated. As the third irradiation has been performed at a different position only period one and two are summed up for the sum of the accumulated charge per cm. No larger variation in anode currents and thus no sign of deterioration was observed at any time.

Year	Time	[μA]	[C]	[C/cm]
2011	≈2.5 months	1.4	10	2.9
2012	≈5 months	3.0	39	11.3
2013	≈4 months	1.3	13	3.8
Sum	≈11.5 months		62	14.2

the endplugs during the 4 months of irradiation can now be compared to the situation where before the active gas volume was irradiated by them. The difference of the accumulated charges for both situations is a measure that can be directly compared to HL-LHC predictions. During four months a charge of 13 C was accumulated on the two wires close to the endcap. From this we estimate that the other beta-electrons were irradiating the endplug with an intensity that corresponds in an active gas volume to an accumulated charge of 17 C and a line charge density of about 5 C/cm. This is the best possible approximation for the impact of the irradiation on the non-active endplugs, as composition, energy-spectra and intensity of the respective components of the background at ATLAS NSW is only vaguely known. Hereby we assume that the interaction of beta-electrons and the interaction of the background at ATLAS NSW is similarly in the endplugs, when an identical amount of accumulated line charge was produced in an active gas volume and when the endplug and the active gas region were irradiated identically long.

No outgassing of the endplug material was observed that created any deterioration of the performance of the drift tubes.

Table 1 shows the current, the accumulated charge and the maximum line charge density in a region of 1 cm along the wire. A simple Monte Carlo simulation was used to estimate the maximum line charge density [C/cm] for each of the tubes. For this we divide the tube along the wire into 1 cm long cylinders and assume that the amount of charge created along the wire within 1 cm scales with the interaction length of the beta-electrons in these cylinders. In the simulation beta-electrons were distributed uniquely under 4π starting at the point source. About 15% of those beta-electrons are emitted within the opening angle of 55 degrees and hit one of the two tubes. For the beta-electrons hitting a tube the interaction length in the active volume of the tube is calculated for each of the affected 1 cm long cylinders. The accumulated charge per investigated cm of wire is then given by the quotient of the integrated interaction length in each of the 1 cm long cylinders by the total interaction lenth of all beta-electrons in the tube times the total accumulated charge. This quantity includes the different rates of beta-electrons entering at different positions into the tube. The last column in Table 1 gives the maximum accumulated charge value per irradiated cm of wire at the wire position closest to the source.

5. Summary

Two ATLAS sMDT drift tubes have been irradiated for about 1 year using a ^{90}Sr beta source. The tubes are from series production and all cleaning processes have been applied according to the prescriptions of the series production.

An integrated charge of 62 C has been accumulated on both wires in a region of about 7.5 cm. This corresponds to a maximum accumulated line charge density of about 14 C/cm. The observed variations of the anode currents follow directly the variations of the temperature of the tubes. Linear temperature correction was applied tentatively to one of the current distributions. This leads to a considerably better stability of the current variations on the percent level and it supports even more that no sign of deterioration of the performance of both drift tubes was observed.

This includes implicitely a study of the natural outgassing of the short polyethylene tubings in the gaslines, which were not irradiated. No negative effect of outgassing was observed.

As well, the occurrence of small localized ageing effects along the anode wire can be excluded with a sensitivity of a few mm, assuming that the ageing effect scales with the intensity of the irradiation. The distribution of the intensity of the beta-electrons is inhomogeneous, it is peaked and concentrated mostly in the area directly above the source. Therefore an easily detectable steady degradation in current by e.g. in total 5% reduction only, from 2.92 μA to 2.77 μA in Fig. 6, could be created by a 2 mm broad region on the anode wire where whiskers are building up slowly. The non-observation of any change in anode currents is a strong evidence that the construction, choice of materials and the operation of those sMDT drift tubes is well under control.

The non-active endplug regions were irradiated by an amount of beta-electrons that would have created in an active gas volume an accumulated charge of 17 C and an accumulated line charge density of about 5 C/cm over four months of irradiation. No outgassing or other performance reducing processes were observed. We compare hereby with the irradiation in an active gas volume, as this can be easily compared to predictions for HL-LHC. The 5 C/cm correspond to 5 years of HL-LHC operation in the innermost region of the ATLAS forward muon spectrometer.

For the potential application of the detectors in the ATLAS NSWs an accumulated charge of 10 C/cm is estimated for 10 years of operation based on the recently measured background rates at a luminosity of 2×10^{34} cm^{-2} s^{-1} for the innermost tubes [1]. The achieved accumulated line charge density 14 C/cm for the active gas volume is well above this limit. Thus sMDT detectors are able to deal with the huge background scenarios given at the innermost regions of the NSWs.

Finally the sMDT technology was not considered for the NSWs. Instead the innermost layer (BIS MDT) of the barrel part of the ATLAS muon spectrometer will be replaced within the Phase-II upgrade of ATLAS by sMDT detectors. At this position the sMDT detectors will experience more than an order of magnitude less background irradiation than in the inner NSW regions. Based on the results of our ageing tests these new detectors will show excellent performance with very high muon tracking efficiencies for the next decades of ATLAS lifetime.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

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