Recent Aging Studies for the ATLAS Transition Radiation Tracker

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***Abstract*—The transition radiation tracker (TRT) is one of the three subsystems of the inner detector of the ATLAS experiment. It is designed to operate for 10 yr at the LHC, with integrated charges of $\sim$ 10 C/cm of wire and radiation doses of about 10 Mrad and 2×10^{14} neutrons/cm^2. These doses translate into unprecedented ionization currents and integrated charges for a large-scale gaseous detector.This paper describes studies leading to the adoption of a new ionization gas regime for the ATLAS TRT. In this new regime, the primary gas mixture is 70%Xe-27%CO_2-3%O_2. It is planned to occasionally flush and operate the TRT detector with an Ar-based ternary mixture, containing a small percentage of CF_4, to remove, if needed, silicon pollution from the anode wires. This procedure has been validated in realistic conditions and would require a few days of dedicated operation. This paper covers both performance and aging studies with the new TRT gas mixture.**

***Index Terms*—Ageing, CFU, gas detectors, tracking, TRT.**

I. Introduction

THE ATLAS transition radiation tracker (TRT) is a straw drift-tube detector that combines electron identification capability with the traditional charged-particle track reconstruction in gaseous detectors. The straws have a diameter of 4 mm with a gold-plated tungsten sense wire 30 μm in diameter and operate in proportional mode at an avalanche gain of about 2.5×10^4.

The layout of the TRT has been optimized for the best performance in terms of track reconstruction and electron/pion separation in the extremely harsh operating conditions expected at the LHC. About 6 m long by 2 m in diameter, the TRT consists of three parts: a central barrel and two end-caps. The first one contains approximately 52 000 long straws of 150 cm length readout at both ends; each sense wire is separated into two halves by a glass wire-joint of about 6 mm length and 0.3 mm diameter. The two end-cap parts consist of about 320 000 radial straws of 37 to 55 cm length. Both barrel and end-cap straws are surrounded by radiator material. In the former case, the radiator consist of randomly distributed polypropylene fibers, while each layer of end-cap straws is placed in between several foils of polypropylene spaced about 20 μm by a polypropylene mesh. Particle identification is achieved by efficiently converting in the Xe-based gas mixture the transition radiation photons that are emitted when a charged ultrarelativistic particle crosses the interface between the two different media, polypropylene and the CO_2 environmental gas, that envelope the TRT straws. The design and construction of the TRT are described in more detail elsewhere [1]–[3].

At the LHC design luminosity of 10^{34} cm^{-2}s^{-1}, the straw counting rates are very large with an estimated average of about 12 MHz and a maximum of 20 MHz for the innermost barrel straws and longest end-cap straws. While most of this counting rate comes from ionising tracks, slow neutrons and low-energy photons also contribute at a significant level. The ionization current density will be 0.15 μA/cm of wire leading to a maximum ionization current per wire of about 10 μA. After 10 yr of operation, the straws will accumulate a radiation dose of about 10 Mrad, and a neutron fluence of up to 2×10^{14} n/cm^2. These numbers include a 50% safety factor for uncertainties in the calculations. The total dose results in unprecedented ionization currents and integrated charges (up to $\sim$ 10 C/cm of wire) for a large-scale gaseous detector.

The original TRT gas mixture was 70%Xe-20%CF_4-10%CO_2 [4]. The CF_4 component was chosen because of its small diffusion coefficient and large drift velocity. Additionally, the CF_4 radicals created in the gas avalanche play an important role in the cleaning of aged wires. As a result, straw lifetimes well exceeding the values needed for 10 yr of operation at the LHC were achieved. However, several studies have demonstrated that the creation

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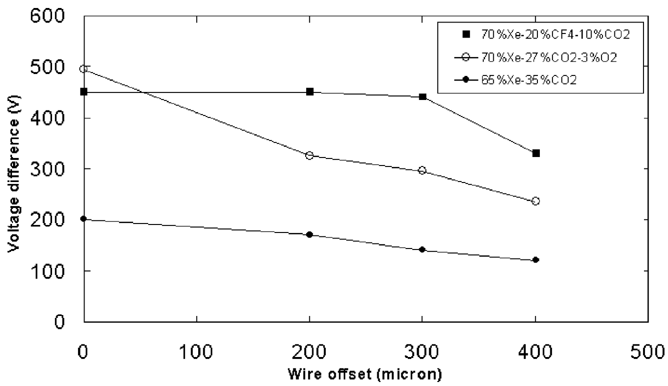

Fig. 1. Voltage difference between the nominal working point and the discharge point for different gas mixtures, measured as a function of the wire offset in the straws. The behavior in Xe-CO_2 65–35 and in the same mixture with the addition of 20% CF_4 or 3% oxygen is compared.

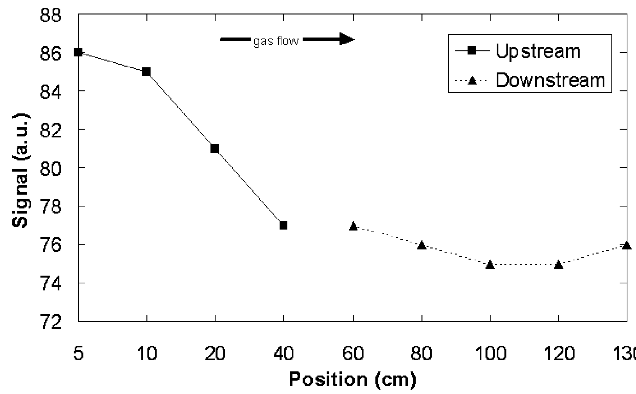

Fig. 2. Gas-gain (in arbitrary units) in the 70%Xe-27%CO_2-3%O_2 gas mixture as a function of the straw length observed after removing the radiation source out of a barrel straw that was uniformly irradiated for 1.5 h at the maximum expected LHC current density of 0.125 $\mu A/cm$, at nominal gas flow rate. The sense wire is separated into two halves by a glass wire-joint and read out at both ends (upstream and downstream in the figure caption, corresponding to the gas inlet and outlet sides, respectively). The accumulation of ozone downstream of the 140-cm-long straw induces a 13% reduction of gas gain.

of HF and other very reactive fluorine-based species occurs when the concentration of moisture in the gas exceeds a certain level, typically $\sim$ 1000 ppm [5]. These reactive species may degrade some materials used in the assembly of the detector, such as epoxy compounds, plastic materials, and fiberglass. In particular, the glass wire-joints (which contain silicon) inside the long barrel straws are etched to the point of breakage by fluorine-containing radicals. HF and/or some long-lived CF_4 radicals are able to catch minute amounts of silicon present in some components, which are then transported into the chamber active volume and deposited on sense wires, thereby reducing the gas gain [5]. This process becomes especially relevant when a closed-loop gas distribution system is needed. Filters and other active purification devices of the gas system are exposed to the accumulation and chemical effects induced by such active species. This can result in a severe and permanent pollution of the gas system, as well as of the detector.

For the original CF_4-contaning gas mixture, the wire-deposit cleaning versus the transport of silicon has been investigated as a function of the operating conditions. It has been found that the balance between these complex processes depends on a careful equilibrium between gas flow, gas purity, local irradiation dose, the width of the irradiated area, and maybe other parameters. To gain some safety margin and reliability during operation at the LHC, a new gas mixture composed of 70%Xe-27%CO_2-3%O_2 has been studied in detail and adopted for operation of the TRT at the LHC. The new mixture does not generate under irradiation chemically aggressive products that eventually would clean silicon-based deposits on wires. Therefore, special measures are required to reach the necessary level of purity for the gas systems components. The validation concept and optimization for selecting components for the construction of the final closed-loop gas system are discussed.

In the case that the TRT would show a significant degradation of performance due to wire aging during its operation at the LHC, cleaning runs of the TRT tracker can be foreseen by using the capability of CF_4 in the high luminosity LHC environment to efficiently clean up aged wires. Several studies are being carried out to determine the integrated charge necessary to restore the gas gain and to find a safe operating lifetime limit of the glass wire-joint of the barrel straws in the aggressive CF_4 environment.

II. TRT Operation and Performance Issues

A critical parameter for safe TRT operation is the voltage difference between the high-voltage operation point, and the point at which discharges begin to occur. The inclusion of 3% oxygen substantially enlarges the operational plateau length of the straws as compared to a more standard binary mixture. Fig. 1 shows as a function of wire offset the voltage difference between the nominal working point and the discharge point for the original gas mixture with 20% CF_4, a binary mixture of Xe-CO_2, and this same binary mixture with 3% additional oxygen. For straws with a 400 μm wire offset corresponding to the maximum tolerable value before a wire is permanently disconnected during the acceptance tests [6], a margin of 220 V is obtained with the new gas mixture, to be compared with 120 V for the binary gas mixture. After taking into account safety factors such as the effect of temperature variations in the detector volume and the effect of highly ionizing particles, a realistic margin of operation is about 170 V, to be compared with 50 V for the binary gas mixture.

The addition of oxygen to the mixture leads to the formation of ozone in the avalanche process. The ozone is a strong absorber of ultraviolet photons and quenches discharges in gas-filled detectors effectively. At the same time, the ozone attaches electrons, therefore, its accumulation in the straw leads to an effective reduction in the signal size. To measure the signal reduction at the LHC intensity, a straw 140 cm long, with the nominal flow rate of ~ 1 volume/hour ($\sim 2.5\ cm^3/min$) was irradiated to give a current density of 0.125 $\mu A/cm$ for 1.5 h. That current density corresponds to the expected maximum current at the LHC. The irradiation was then turned off and the gas gain quickly measured, while the distribution of ozone was still in its steady state. The results are shown in Fig. 2. The gas-gain over the first 50 cm of the length of the straw is reduced from 0 to 13%, and for longer lengths, the loss of gain remains stable at $\sim 13\%$. This would indicate that the creation of ozone and dissociation under irradiation reach an equilibrium at the middle of the total straw length. The actual ozone concentration corresponding to this amplitude loss is about 150 ppm. For the shorter

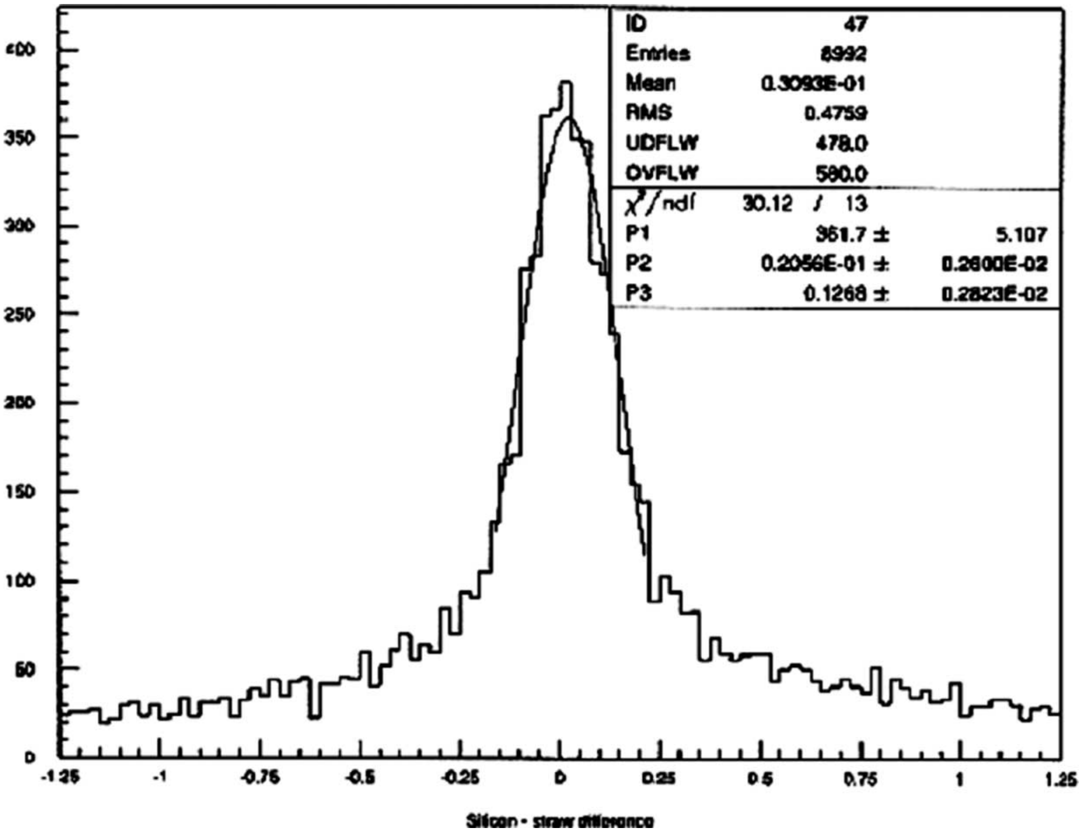

Fig. 3. For 20-GeV test-beam pions and a straw counting rate of 18 MHz, distribution of the residuals obtained from the straw drift-time measurements, with respect to the beam track defined by a silicon telescope, after conversion of the straw drift-time measurement to a radial distance from the straw center in mm. The drift-time accuracy obtained is 127 μm and the efficiency is 51%. The measurement was taken with a gas mixture of 70%Xe-27%CO_2-3%O_2.

straws in the end-cap modules, this effect is limited and below 10%. This magnitude of amplitude degradation has no significant impact on the TRT performance.

The performance of the ASDBLR and DTMROC ASICs [7] has been successfully demonstrated with several prototype barrel and end-cap modules in system tests [8], [9]; electron identification [10], [11] and tracking [2], [12] performances have been studied under a variety of operating conditions in beam tests. Fig. 3 shows, as an example, the residuals distribution obtained from the straw drift-time measurement, after conversion to a radial distance from the straw center. This measurement has been taken during a beam test with 20-GeV pions and with the straws irradiated at a counting rate close to 20 MHz. The drift-time accuracy and efficiency, defined, respectively, from the distribution shown in Fig. 3 as the rms σ of a Gaussian fit to the peak and the fraction of selected measurements lying within a $\pm 2.5\sigma$ around the peak position, are, respectively, 127 μm and 51% at this maximum straw counting rate. Without any background counting rate, these values improve to 102 μm and 80%, respectively. These results were in fact obtained with the final version of the analogue front-end chip, but with a simplified digital readout yielding a somewhat worse efficiency for small pulses. Using the full electronics readout chain on a sector prototype equipped with 384 channels, the drift-time efficiency at low counting rate was found to be 88% in good agreement with expectations from Monte Carlo simulations. The drift velocity in the new gas is about 10% less than in the original CF_4-containing gas mixture. As a result, the drift-time accuracy is slightly better, and the occupancy is increased by, at most, 6%.

III. Straw and Wire Aging

Many aging studies have been repeated to study the new gas mixture. Several straw detectors connected to clean gas systems have been irradiated at different current densities. Fig. 4 shows the electron microscope picture of an irradiated portion of a wire, uniformly irradiated over 20 mm of its length for more than 2 m to reach an accumulated charge of 11 C/cm. The surface of the wire appears clean and free of any deposits, as it was confirmed by the Energy Dispersive X-ray Analysis (EDX). To collect such a large charge in a reasonable amount of time, the experiment started with a current density of 0.1 μA/cm, the maximum expected current at the LHC. After 100 h of operation, the current density was increased to 1 μA/cm. After 2 C/cm of total accumulated charge, the current was again increased to 3 μA/cm. Gas-gain measurements along the full length of the wire were performed regularly throughout the whole duration of the test. Neither anode nor cathode damage was observed.

The oxygen-containing mixture has the capability of cleaning hydrocarbon-based deposits. Fig. 5 shows the relative signal amplitude along a straw after irradiation during 30 h in 70%Ar-27%CO_2-3%C_2H_6. In this mixture, the gas-gain is reduced by about 60% over most of the irradiated length. The irradiation of this same wire in the oxygen-containing gas

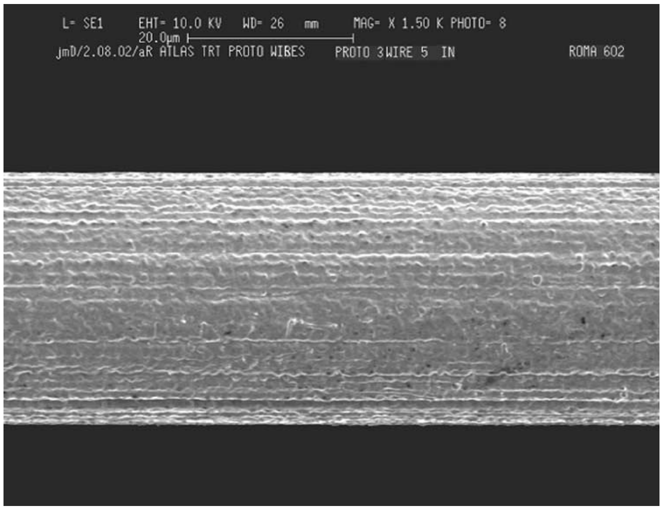

Fig. 4. Picture taken with an electron microscope of a portion of wire that has been irradiated during 2 mo to accumulate an integrated charge of 11 C/cm in the new gas mixture (70%Xe-27%CO_2-3%O_2). No damage or deposits on the surface are observed. The EDX analysis did not show the presence of any contaminant.

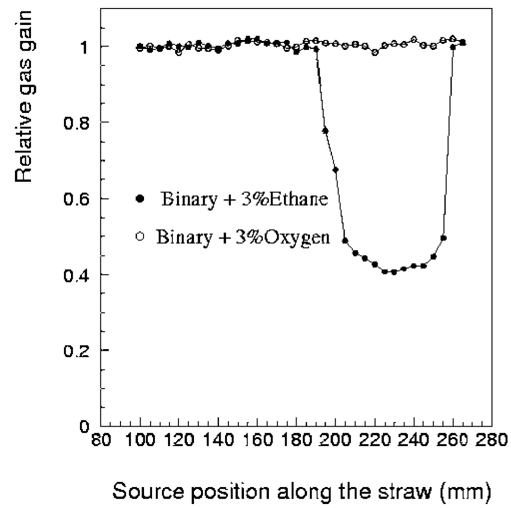

Fig. 5. Relative signal amplitude along a straw irradiated during 30 h in 70%Ar-27%CO_2-3%C_2H_6. The gas flow direction is from left to right in the figure. The irradiated wire length was 100 mm, between 150 and 250 mm on the x-axis of the plot. The open dots show the results of the same scan performed after irradiating the aged straws during 18 h in the new oxygen-containing gas mixture.

mixture during 18 h restores completely the gas gain to its original value, as also shown in Fig. 5. The small concentration of ozone created during the avalanche process is probably large and reactive enough to remove thin hydrocarbon-based layers.

Silicon-based deposits have been found in some straw detectors tested with the new gas mixture and studies are in progress to understand the origin of these effects. Even if it is not often possible to identify the exact source of silicon contamination, it is rather clear that the new TRT gas mixture is much more sensitive to silicon pollution than the original one. No definite conclusions have yet been found concerning the impact of silicon, from external sources or from the minute quantities present in the TRT straw cathode material, as reported in [5]. In any case, with the new gas mixture, it is clearly mandatory to put even more effort in the validation of all components in contact with the gas, in the detector and associated gas systems; special attention is required to accumulation effects in the final closed-loop gas system. These effects may even depend on the straw length, indicating that the gas-system validation tests can only be performed using fully irradiated, realistic, full-size straw setups. Despite all efforts, it is very difficult to guarantee the required cleanliness conditions during 10 yr of operation. As will be discussed later, only the periodic use of a cleaning gas able to remove possible deposits of Si-based contamination from the wires, therefore, probably with a significant concentration of CF_4, would preserve stable operation of the TRT detector over many years.

IV. Cleaning Gas

The effect of CF_4 on the cleaning of deposits versus the transport of silicon has been observed and studied as a function of the operating conditions. It has been found that a small addition of CF_4 to the gas in the high-luminosity LHC environment is efficient to clean up aged wires. Extensive studies are been carried out in order to understand if this capability can be used to periodically clean the TRT detector during its operation at the LHC, if needed. The present status of these studies is discussed here.

In these tests, straws were aged in an Ar/CO_2 mixture bubbled through Si-containing oil. The straws were illuminated with ^{90}Sr sources over their full length, though the radiation dose was stronger at the center, and the gas gain was monitored regularly at 26 different points along the straws. Fig. 6 shows in 12 successive plots labeled from a) to l) the time evolution of the straw gas gain (in the first plot in arbitrary units and after as normalized signal amplitude) in 26 monitored positions along the wire (z axis). Initially, the straw is filled with a Si-contaminated Ar-CO_2 gas mixture, and aging begins immediately, as shown in plots a) to f); the rate of aging is larger at the center of the wire where the radiation dose was stronger. When the gas gain has decreased by about 20%, the Si-contamination was removed and 8% CF_4 was added to the original gas mixture. Soon after, the gain recovery is visible, as shown successively in plots g) to l). A few hours are needed to reach the natural end of the cleaning cycle, as shown in plot l). Full recovery is achieved over most of the straw length, except at the gas inlet. This would indicate that, possibly, the concentration of chemically active F-based radicals at the beginning of the straw is not sufficient to completely etch away the silicon deposits. The inspection of the wire surface with an electron microscope confirmed the cleaning effect.

Several studies have been carried out to determine the safe operating lifetime limit of the glass wire-joint in the barrel straws in CF_4 mixtures, as a function of the CF_4 fraction (16%, 8%, and 4%), the moisture level, the gas gain, and the irradiation dose. The failure of the wire-joint is defined as the quantity of accumulated charge in C/cm of wire for which, after a loss of wire tension due to etching of the glass wire-joint, the wire breaks. From this and other sets of systematic measurements, the following has been concluded.

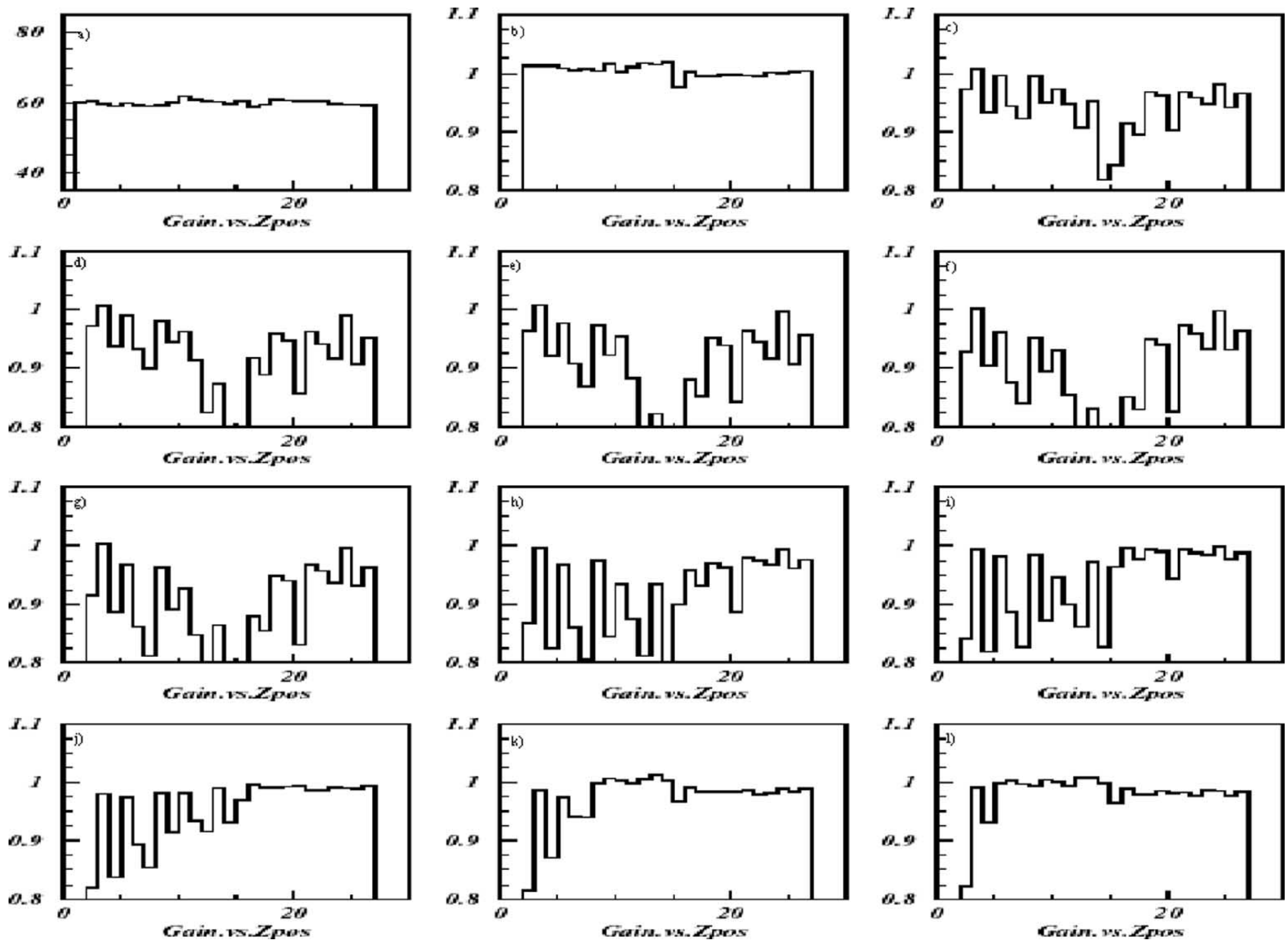

Fig. 6. Gas gain in arbitrary units in a barrel straw, as measured over 26 points along its length (z-axis) and as a function of time (successive plots). The straw was first irradiated along its full length with a ^{90}Sr source and flushed with an Ar-CO_2 gas mixture contaminated with silicon; the gas gain along the straw during that period is shown in plots from a) to f). The radiation dose was stronger at the center of the straw. The straw was then flushed with a clean Ar/CO_2 gas mixture containing in addition 8% CF_4. Plots g) to l) show the gas gain along the full straw length during that caning run. The recovery of the signal amplitude is clearly visible at the end of the run, as seen in plots k) and l).

- Silicon deposits can be etched away, with the exception of the very first centimeters of the straw close to the gas inlet; this would require flushing the cleaning gas in the opposite direction in order to have completed cleaned wires.
- After a cleaning run, the gas gain is restored to its original value.
- No residual effect is seen when the gas is switched back to a non-CF_4 mixture.
- The wire-joint failure limit for different concentrations of CF_4 are ~ 0.15 C/cm for 4%, 0.10 C/cm for 8%, and ~ 0.05 C/cm for 16%.
- It has also been observed that the wire-joint failure limit is roughly proportional to the water concentration in the gas.

From these observations, it is estimated that about 30 cleaning days can safely be performed in ATLAS for 4% to 8% concentration of CF_4 in the cleaning gas. Thus, one cleaning run per year, if needed, seems realistic. Typically, a cleaning run would be performed during standard LHC operation, with water content below 1000 ppm, and in gas-flushing mode to avoid pollution of the closed-loop gas system. This mode of operation would still allow efficient tracking but not transition radiation due to the replacement of xenon by argon. The final closed-loop gas system is being designed to allow reversal of the flow of the cleaning gas. Presently, it is being studied how to determine when a cleaning run would be needed and how often this can be expected during running at the LHC.

V. Gas System

A complex issue for the safe operation of gaseous detectors is the cleanliness of the gas supply system, especially when closed-loop systems are required, as is the case for the TRT due to the high cost of the xenon gas. The components used to build the gas system have to be selected with care to avoid unexpected pollution of an initially clean gas mixture. The component choice should include the selection of materials, which display low outgassing and are chemically compatible with the gas mixture. Avoiding pollution during the assembly process requires the establishment of clean and safe methods for assembly and operation of the system. These principles should be used to assemble, not only the final gas system, but also any system supplying gas during the production and testing of modules at the various sites.

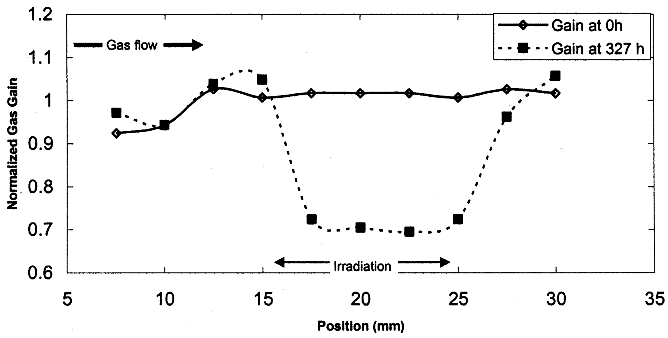

Fig. 7. Response of a straw tube irradiated in a validated clean gas system, where a Voegtlin type 2004 flowmeter has been inserted. The gain drops by $\sim 30\%$ in about 370 h of irradiation.

A major problem when selecting clean gas components is the difficulty of finding complete specifications and product descriptions. Even more, once an adequate product has been found and successfully tested following a strict validation process that includes long-term aging tests of counters, it is difficult to trust the cleanliness conditions for larger quantities.

The TRT consistently has followed a fixed validation policy for all components used in the gas systems. A component is considered validated if, after performing an aging test with TRT straws in a clean gas system where the component under test has been introduced, no aging is detected after ~ 500 h of irradiation at the nominal gas flow and current density of one volume exchange per hour and 100 nA/cm, respectively. Taking into account the numerous gas systems at the various sites and the complexity of the final mixer, an optimization of the validation procedure is under study aimed at minimizing the testing time. The conditions of operation during validation tests should reveal rapidly any amplitude degradation. Many tests have been carried out and the following observations can be made, although more time is required to reach definite conclusions.

- The aging rate does not depend on the gas mixture for Ar-CO_2, Ar-CO_2-O_2 and Xe-CO_2-O_2.
- Aging seems to appear faster for gas flows significantly higher than the nominal one of one volume exchange per hour. When the components under test are inserted as close as possible to the irradiated straws flushed at 10 times the nominal gas flow, aging effects are observed in less than 100 h for contaminated components.
- Large current densities appear to accelerate the aging process. Further studies are needed to verify whether this tendency is universal for all setups and all types of pollution.
- Usually, for Si-pollution, aging, i.e., gain drop induced by silicon deposits on the wire, is observed only at the beginning (in terms of gas flow) of the irradiated area.

Taking into account these observations, a typical validation run for a component under test will be performed in 70%Ar-30%CO_2 flushed at 1.5 $\mathrm{cm^3/min/straw}$, which corresponds to 10 times the nominal flow, at nominal gas gain and at a current density of 100 nA/cm. The straw will be irradiated over a length not more than 1 cm, and for about 150 to 200 h. Fig. 7 shows, as an example, the response of an irradiated TRT straw in a validated clean gas system, where a presumably grease-free Voegtlin flowmeter type 2004 cleaned for oxygen applications has been inserted. The gain drops by $\sim 30\%$ in 370 h of irradiation, invalidating the use of this component in any of the gas systems used during production, quality tests and operation of TRT modules. Many other components, such as stainless steel pipes, electronic and mechanical flowmeters, valves, etc., have been checked and validated in aging tests that have successfully lasted for more than 1000 h in both the binary Ar/CO_2 and the final oxygen-containing gas mixtures. Table I lists some of the tested components. Presently the validation concept and further optimization, for the selection of components for the construction of the final closed-loop gas system, are being worked out.

VI. Summary

Loss of performance due to silicon pollution has been a concern for the operation of the ATLAS TRT at the LHC over many years. CF_4-containing mixtures have therefore been considered as very attractive in terms of aging. The competition between the polymerization and formation of deposits and the etching process usually slows down conventional aging effects. It appears that etching is the favored process, probably because CF_4 dissociates in species that have enough energy to break chemical bonds in polymers which are then reduced to stable, volatile products, eventually removed by the gas flow. This belief led many years ago to think that the use of CF_4-based mixtures would allow the requirements for cleanliness in gaseous detectors under high radiation to be relaxed. At present, it has been shown that such a choice might have undesirable consequences. Etched silicon-based compounds are effectively removed but distributed ubiquitously, polluting the detector and promoting heavy polymerization. Many nonmetallic components of the gas system and assembly materials can be affected. For instance, the glass wire-joints (containing silicon) inside the long barrel straws can be etched to the point of breakage. These effects depend on the moisture level, gas gain, irradiation conditions, and the fraction of CF_4 in the gas mixture.

A new TRT gas mixture composed of 70%Xe-27%CO_2-3%O_2 has, therefore, been proposed and validated over the past two years. The 3% oxygen adds a significant operational safety margin as compared to a simpler binary mixture, while keeping aging phenomena in the harsh LHC environment at a minimum. With this new gas mixture, special measures are required to reach the necessary level of purity for the gas-system components. Time-consuming validation tests for all components of the final closed-loop gas system are being defined and carried out. An optimization of these tests is under study to be able to find suitable components in a reasonable amount of time.

Periodic cleaning runs of the TRT modules will be possible, if needed, by temporarily adding CF_4 to the gas mixture to use its capability of efficiently cleaning up aged wires in the high luminosity LHC environment. Since the glass wire-joints of the barrel straws are exposed to the etching process, the amount of CF_4 and the time to perform these cleaning runs should be optimized. It has been found in a set of systematic measurements that the failure limit, defined as the accumulated charge in C/cm

TABLE I
GAS SYSTEM COMPONENTS WHICH HAVE BEEN SUCCESSFULLY VALIDATED IN AGING TESTS IN 70%XE-30%CO_2 AND 70%XE-27%CO_2-3%O_2 FOR MORE THAN 1000 H

Element	Details	Preparation	Aging detected in Ar-CO_2	Aging detected in Xe-CO_2-O_2
Pipe	Stainless steel 316L (CERN store)	Cleaning of edges in isopropyl alcohol	No	No
Pipe	SS Flexible	Cleaning (pump), degreasing (ALMECO), demineralized water, N_2 drying	No	-
Fitting	Gyrolok	Cleaning in ultrasonic bath with isopropyl alcohol	No	No
Flowmeter	VOEGTLIN V100-80A	Cleaning in ultrasonic bath with isopropyl alcohol	-	No
Flowmeter	Gillmont ACCUCAL	-	No	No
Mass flow controllers	BROWNKHORST	-	-	No
Pressure regulator	SCOTT C21-8	-	-	No
Pressure regulator	SCOTT 218	-	No	-
Valve	Swagelok SS-43S6MM-SC11	-	No	No
Valve	SS Needle valve GYROLOK (CERN store)	-	No	No

of wire where wires would break due to etching of the glass wire-joint, is proportional to the concentration of CF_4 in the mixture, as well as to the moisture level. From the measurements to-date, it is estimated that about 30 cleaning days can safely be performed in ATLAS with Ar/CO_2 and 4% or 8% CF_4. Thus, one cleaning run per year, if needed, seems realistic. Typically, a cleaning run would be performed during standard LHC operation, with controlled water content below 1000 ppm, and in gas flushing mode to avoid polluting the recirculation system. This configuration would still allow the TRT to perform efficient tracking but not transition radiation detection.

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