

Radiation Tolerance of the LHCb Outer Tracker: in the Lab and in the Forward Region at the LHC ¹

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Abstract

During the detector construction phase between 2004 and 2006, it was discovered that the LHCb Outer Tracker (OT) detector suffered from gain loss after irradiation in the laboratory at moderate intensities. Under irradiation an insulating layer was formed on the anode wire. The aging was caused by contamination of the counting gas due to outgassing of the glue used in construction namely araldite AY103-1. The gain loss was concentrated upstream the gas flow, and at moderate irradiation intensity only. The aging rate was reduced by longterm flushing and by the addition of a few percent of O₂ to the gas mixture. Furthermore, applying a large positive high voltage (beyond the amplification regime) has shown to remove the insulating deposits without damaging the wire surface. This paper presents the history of the developments together with the characteristics and the culprit of the aging phenomenon and the resulting detector performance in situ.

Keywords: Tracking detectors, Gas detectors, Straw tubes, aging

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1. The LHCb Outer Tracker

The LHCb experiment has provided a wealth of CP violation and rare *B*-decays measurement fulfilling its promise and beyond, surpassing its original physics programme with world-leading results in the areas of heavy-ion physics and in the high-*p_T* electroweak sector. These phenomenal successes were possible despite the original worries regarding the radiation hardness of the Outer Tracker (OT) detector, a gaseous straw tube detector [1] that covered an area of approximately 5x6 m² with 12 double layers of straw tubes.

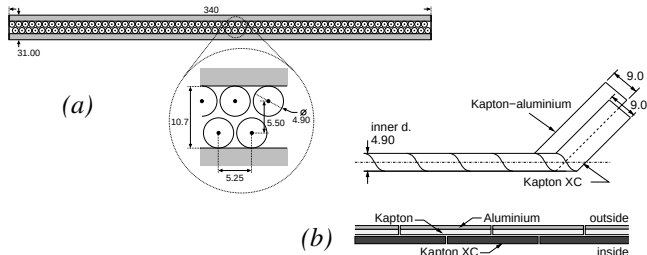


Figure 1: (a) Module cross section. (b) The straws were wound using two foils, kapton-XC and a laminate of kapton and aluminium.

The straw tubes were 2.4 m long and 4.9 mm in diameter, and were filled with a gas mixture of Ar(70%)-CO₂(30%). The anode wire was made of 25μm gold plated tungsten wire, whereas

the cathode consisted of an inner foil of 40 μm electrically conducting carbon doped Kapton-XC and an outer foil of 25 μm Kapton-XC with 12.5 μm aluminium. The straws were glued to sandwich panels with 120 μm carbon-fibre skins and a 10 mm Rohacell core. Finally, the panels were joined by 400 μm thick carbon fibre sidewalls, resulting in a standalone detector module. A sketch of the module layout is shown in Fig. 1. The panels and the side walls were covered by a laminated foil of 25 μm Kapton and 12.5 μm aluminium to guarantee gas-tightness of the box and to provide a closed Faraday cage. Spacers at the ends of the module separated the two panels apart and pass the gas to the module. All glueing steps were performed using Araldite AY103-1 with the hardener HY991, cured at room temperature. To enhance the viscosity silica bubbles are added.

The module production had started in April 2004 and extensive quality and performance measurements were performed. For example, signal propagation and analog electronics characteristics were studied extensively with the use of a 2 mCi ⁹⁰Sr source (with 1.7cm diameter collimator), inducing a current of 3 nA. In June 2005 it was discovered that, despite extensive aging tests in the R&D phase [2], the module used for these tests suffered from gain loss at the same location as the irradiation. These tests were not performed under well-defined conditions and numerous external pollutants were considered. In October 2005 a 20 mCi ⁹⁰Sr source was used in a different setup to study various gas mixtures, (inducing about 100 nA per wire for about 12 hours) and again gain loss was observed, and a new systematic aging study campaign started. In the meanwhile module production finished in November 2005. This paper summarizes the findings, also described in Refs. [3], [4] and [5].

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2. Aging Phenomenon

2.1. Irradiation and monitoring setup

Irradiation tests were carried out on a small selection of final modules using a 2 mCi ^{90}Sr source. The high voltage on the anode wires was set at 1600 V and the gas flow (with a mixture of 70/30 Ar/ CO_2) was 20 l/hr, corresponding to approximately one volume exchange per hour. The source was collimated by a hole with a diameter of 6 mm at a distance of 5 mm from the module, resulting in an irradiated area of approximately $6 \times 6 \text{ cm}^2$.

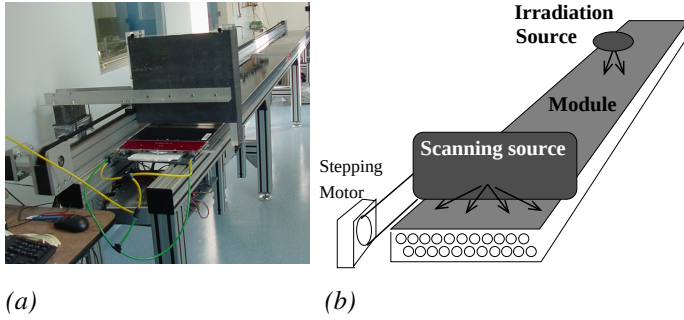


Figure 2: (a) Photograph of the irradiation setup. The scanning source with which the performance before and after irradiation is measured is also shown. (b) Schematic view of the irradiation and scanning setup.

Before and after irradiation the response of each wire in the module was checked with a 20 mCi ^{90}Sr source. The full module width was irradiated in steps of 1 cm along the length and the corresponding wire current was measured and recorded. The setup is depicted in Fig. 2. A typical example of the gain loss after an irradiation of 20 hours is shown in Fig. 3b. The gain loss was quantified by comparing the 2-dimensional current profile before and after irradiation, by means of dividing the two current profiles. The observed gain loss shows several distinguishing features:

- The gain loss was not proportional to the source intensity: directly under the source the gain loss was less severe compared to the periphery. The gain loss for each measurement (corresponding to a pixel of $0.5 \times 1 \text{ cm}^2$) is shown as a function of the irradiation intensity in Fig. 3c. This dependency was unchanged when the module was irradiated at different values of the high voltage, or with different source strengths.
- The gain loss occurred mainly upstream the source position, and was worse for larger gas flow. Presumably due to the creation of ozone in the avalanche region, the gain loss was prevented downstream, see Section 4.2.
- The gain loss was large, upto 25% for an integrated dose of 0.1 mC/cm at an intensity of 2 nA/cm .

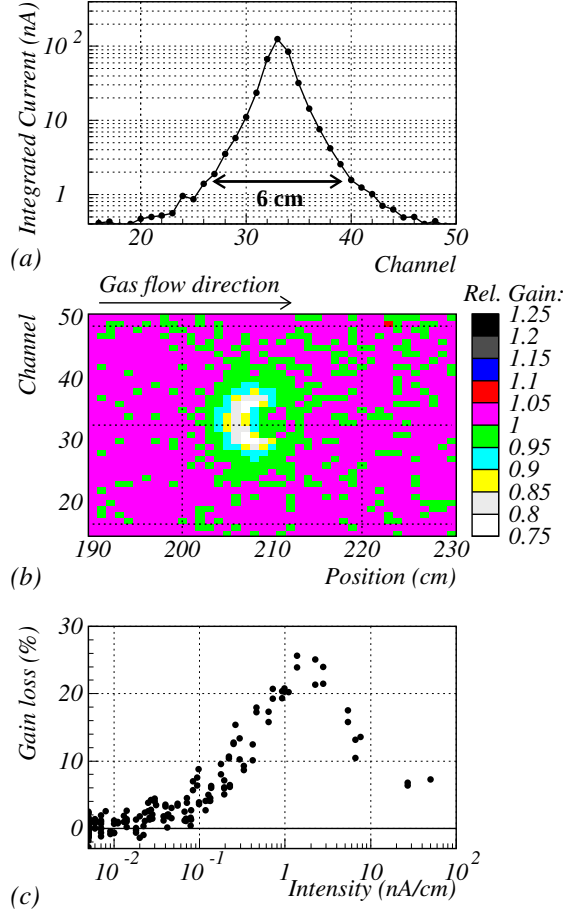


Figure 3: (a) The integrated current per wire during irradiation. (b) The ratio of two ^{90}Sr scans before and after irradiation shows the relative gain loss after an irradiation of 20 hours. The source was centered on channel 32 on position 208cm. (c) The gain loss is shown for each measurement (pixel of $0.5 \times 1 \text{ cm}^2$) as a function of the source intensity in that pixel. The gain loss was highest at moderate intensity, around 2 nA/cm .

2.2. Wire inspection and outgassing

Samples of the anode wire were removed from an irradiated module for inspection with a sampling electron microscope (SEM). An irradiated wire with observed gain loss as described in the previous section, was compared with an unirradiated wire. An electrically insulating coating was found on the irradiated wire, see Fig. 4. The deposits were analyzed by means of energy-dispersive X-ray spectroscopy (EDX) which revealed the presence of carbon and indirectly that of hydrogen.

The outgassing of AY103 and AY103-1 was investigated by placing cured glue samples in a vacuum chamber. The residual gas emitted by the glue was analyzed with a quadrupole mass spectrometer. The quadrupole mass filter sorts the produced ions according to their mass/charge ratio up to a value of 200 u/e . The resulting spectra are shown in Fig. 5. The traces of DBP and di-isopropyl-naphthalene are identified in the mass spectra of AY103 and AY103-1, respectively.

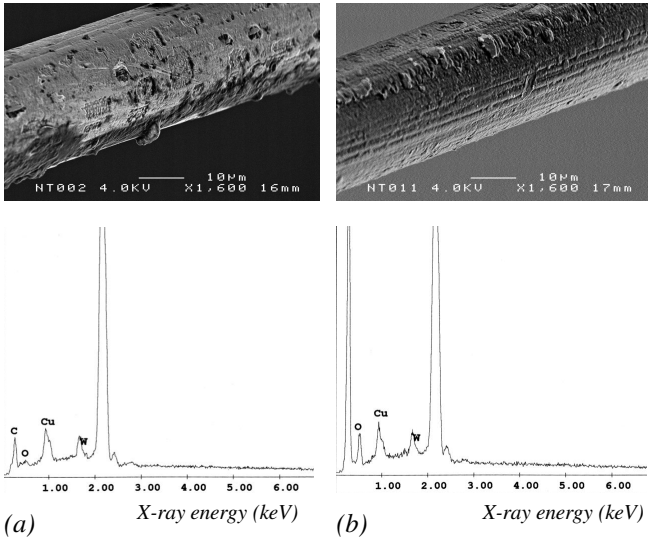


Figure 4: (a) A SEM picture and EDX spectrum is shown for a sample of unirradiated outer tracker anode wire. (b) The same for an irradiated wire sample. A layer with a wax-like structure is observed, and a large amount of carbon is seen in the EDX-spectrum, indicating the presence of carbon-hydrates.

3. The Culprit

A comprehensive review of materials in gas detectors can be found elsewhere [6]. After extensive aging tests before 2004 the glue AY103 was identified for the module construction. The manufacturer produced the last batch of AY103 with plastifier dibutyl phthalate (DBP) in 2003, before switching to AY103-1 with plastifier di-isopropyl-naphthalene.

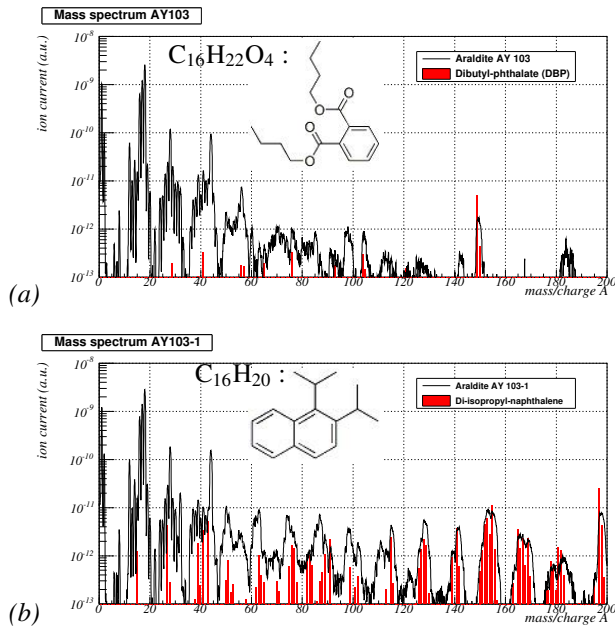


Figure 5: (a) In the mass spectrum of AY103 traces of the plastifier dibutyl-phthalate (CAS nr. 84-74-2) are identified. (b) In the mass spectrum of AY103-1 traces of the plastifier di-isopropyl-naphthalene (CAS nr. 38640-62-9) are identified. The molecular structure of the plastifiers is also shown.

To identify the origin of the insulating deposits an aluminum test module was constructed with a minimum of components, containing the straw tubes, wires, wire locators and feed-through PCB's only. The module was sealed with a large O-ring. No signs of gain loss were observed after 480 hours of irradiation with maximum intensity of 75 nA/cm, corresponding to an integrated dose of approximately 0.13 C/cm.

In total seven straws were injected with AY103-1, three straws with AY103 and three straws with AY105-1 (Fig. 6a). The remaining 19 straws do not contain glue and are used as reference.

Subsequently, the module was irradiated with a 20 mCi ^{90}Sr source collimated such that the source illuminates the module over the full width. Each straw was irradiated over a length of approximately 4 cm, resulting in an irradiated area of approximately $34 \times 4 \text{ cm}^2$. The high voltage on the anode wires was set to 1600 V and a gas mixture of Ar(70%)-CO₂(30%) was used. This corresponds to a gas amplification of approximately 8×10^4 . The gas flow was set to 20 l/hr, corresponding to approximately one volume exchange per hour. Before and after irradiation the response of each wire in the module was measured with a scanning source. The full module width was scanned in steps of 1 cm along the length, and the corresponding wire current was measured and recorded.

A strong reduction in the signal response due to the irradiation was observed in the channel containing AY103-1, extending to a large area upstream the source position. Also the channel with AY103 showed a drop in the signal response upstream the source position, albeit to a lesser extent compared to the epoxy containing di-isopropyl-naphthalene, and limited to the region where the glue was inserted. The channel containing the epoxy without any plastifier, AY105-1, did not exhibit a gain drop after irradiation.

The summary of all results for the 32 straws irradiated in the first session is given in Fig. 6b, that shows the ratio of the response before and after irradiation. Different straws were injected with glue at three different dates, (1 week, 4 weeks and

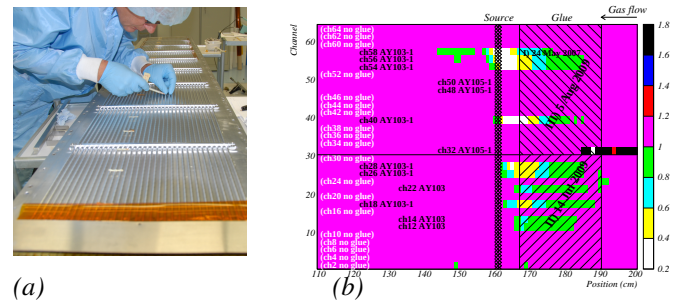


Figure 6: (a) Photograph of the openable module during glue injection into a straw using a syringe. (b) The ratio of the response before and after the first irradiation in August 2009 is shown for the full module. The type of injected glue is indicated per straw. The glue was injected between positions 167 cm and 190 cm on three different dates, as indicated in the figure. The source illuminated the module over the full width at position 161 cm. The gas flows from right to left.

2 years prior to irradiation, during which the module was not being flushed in the periods Jan-Apr 2008 and Mar-Jul 2009) but no dependence of the ageing rate with AY103-1 on these dates was observed, indicating that outgassing of the plastifier di-isopropyl-naphthalene was proceeding slowly. The straws containing AY103-1 consistently showed a large drop in signal. Fast ageing effects have also been observed [7] with other aromatic hydrocarbons, like toluene and styrene with a molecular structure similar to that of naphthalene.

Finally, a full scale OT module was constructed with AY105-1. The module was irradiated over the full width at three different positions for 500, 1060 and 980 hrs. Given the point of highest irradiation intensity, this corresponds to an accumulated charge of 0.13, 0.28 and 0.25 C/cm, respectively. A negligible gain loss of $5\% \pm 2\%$ was observed, indicating that this was not related to the fast aging caused by AY103-1.

We concluded that outgassing of the plastifier in Araldite AY103-1 was the origin of the carbon deposits on the anode wire, resulting in gain loss in the detector.

4. Beneficial treatments

The *shape* of the dependency of the gain loss on the irradiation intensity remains unchanged when parameters of the irradiation tests are changed, such as: high voltage, source type, source intensity, gas flow, gas mixture, humidity, irradiation time, or flush time. However, the maximum gain loss *does* vary, depending on some of these parameters. Beneficial effects on the maximum gain loss are described in this section.

4.1. Flushing

Given the fact that the araldite AY103-1 glue used in construction was a necessary ingredient to cause the gain loss in the OT detector, long term flushing was expected to transport away the vapours originating from outgassing of the glue. Indeed, Fig. 7 shows the maximum gain loss caused by an irradiation of 20hrs as a function of flush time. The aging rate decreased significantly. All OT modules had been flushed continuously since the completion of installation in the LHCb experiment in Spring 2007.

In addition, experiments in the laboratory showed that heating the modules at 40°C might have accelerated the outgassing of the glue, although the effect on the aging rate differed from module to module. All modules in the experiment were heated for two weeks at 35°C while flushed at 0.5 volume exchanges per hour.

4.2. Additives

Oxygen has been used in other HEP experiments in the context of irradiation damage and gas detectors [? ?]. Tests with the OT show that the aging rate for gas mixtures with O_2 is reduced by approximately a factor two. The improvement in aging rate with flushing time was similar for the nominal gas mixture Ar/ CO_2 70/30, as compared to the gas mixture with a few percent O_2 added, see Fig. 7. The amount of oxygen had

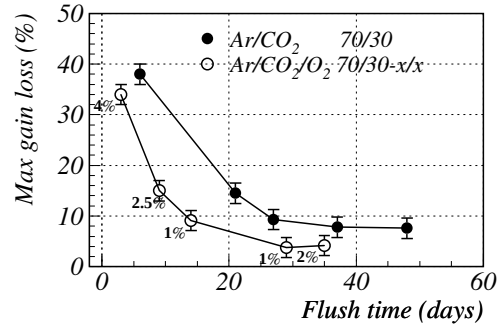


Figure 7: The maximum gain loss decreased as a function of flushing time. Also, the aging rate was smaller when a few percent of oxygen is added to the gas mixture, varying between 1% and 4%. The improvement did not strongly depend on the exact amount of oxygen.

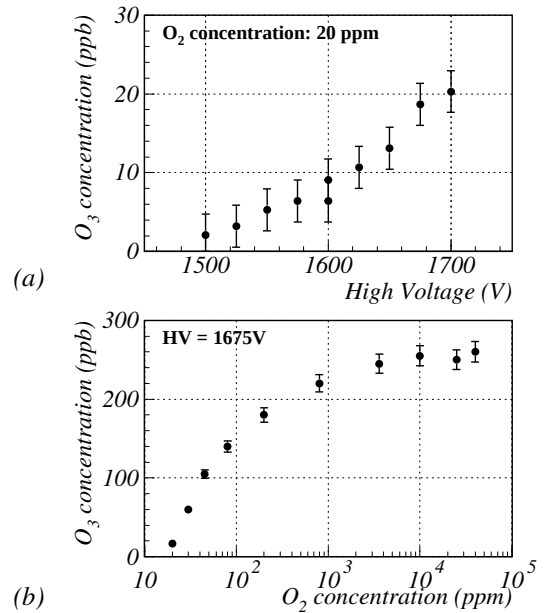


Figure 8: (a) The ozone concentration increased for larger values of the high voltage, i.e. for larger amplification, indicating that ozone was produced in the avalanche. (b) The ozone concentration as a function of oxygen concentration. Above 1% O_2 the ozone concentration was constant.

been varied between 1% and 4%, but the improvement did not strongly depend on the exact amount of oxygen.

Due to the small diameter of the OT straw tubes, the average signal height at the anode wire was only reduced by 11% (29%) when 2.5% (4.5%) O_2 was added to the gas mixture. Studies performed with the Garfield and Magboltz programs indicated that the drift speed was not affected.

A sensitive ozone (O_3) meter had been placed at the gas outlet during irradiation tests of OT modules. The ozone concentration increased with increased high voltage (Fig. 8a), indicating that ozone was formed in the avalanche region. The production of ozone under the source was presumably the reason that

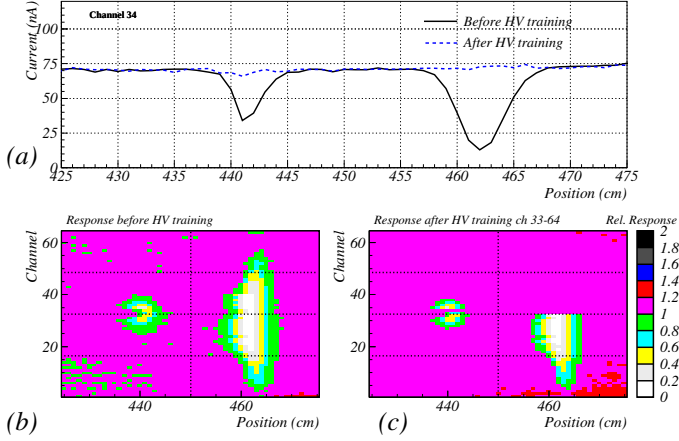


Figure 9: (a) The signal response is shown for one channel before and after applying a large positive high voltage of 1940 V. The signal decrease around 441 cm and 462 cm is due to gain loss induced by irradiation tests. (b) The signal response is shown for all 64 channels before the high-voltage treatment. (c) The signal response is shown for all 64 channels after applying a high voltage of 1940 V to channels 33-64. The full signal gain is recovered in most places.

no gain loss is observed downstream of the source. This was consistent with the observation that the aging rate was larger for increasing gas flow, when the produced ozone was transported away more efficiently.

The concentration of O_3 had also been determined for various oxygen concentrations, see Fig. 8b. For increasing oxygen concentration, larger amount of ozone had been measured, which might explain the beneficial effect of oxygen on the aging rate. Above 1% of oxygen, the ozone concentration did not increase, supporting the observation that no difference in the aging rate was observed between 1% and 4% O_2 .

4.3. HV training

Once the detector suffered from gain loss caused by the irradiation, the insulating deposits could be removed by applying an high voltage at elevated values. Applying a reverse bias around -1450 V leads to fluctuating large dark currents above 1 μA . After a period of 24 hrs the gain was recovered. Similarly, a positive bias between 1850 V and 1920 V leads to dark currents of about 10 μA per wire. The gain was recovered in most cases after 20 hours. The microscopic mechanism was unclear, and could have been related to plasma sputtering of the wire surface or elevated temperatures at the location of the discharges.

The procedure with positive voltage had the advantage that the currents were more stable, being less sensitive to trips in the power supply. Secondly, since the OT detector was operated with positive bias, power supplies for positive voltages were readily available for the whole detector.

Potential damage to the anode wire had been investigated in the scanning electron microscope after a treatment of 35 hrs at 1880 V, subject to a current of 50 μA . No signs of mechanical damage to the gold layer were observed. In addition, the relative peak heights of gold (Au) and tungsten (W) in the EDX spectrum indicated that the gold layer was undamaged.

5. Detector performance in LHCb

The performance of the Outer Tracker detector in Run-1 and Run-2 of the LHC has been according to (or better than) design specifications [1, 8]. The single hit efficiency was measured to be above 99%, while the noise rate was below 40 kHz (which implies a 0.1% occupancy of noise hits per event at 40 MHz readout rate). Due to the low amplifier threshold setting, the effect of time-walk was minimized, and a time resolution of 3 ns was obtained, leading to an intrinsic position resolution of better than 180 μm . The relatively large straw diameter of 4.9 mm would lead to unacceptably large detector occupancies at the five-fold increased instantaneous luminosity of $2 \times 10^{33} cm^{-2} s^{-1}$ at Run-3 of the LHC, which necessitated the replacement of the Outer Tracker by the Scintillating Fiber Tracker.

6. Conclusion

The LHCb Outer Tracker detector modules had shown to suffer from significant gain loss after irradiation in the laboratory at moderate intensities, peaking at about 2 nA/cm. During irradiation an insulating layer containing carbon is formed on the anode wire. The aging is caused by contamination of the counting gas due to outgassing of the glue used in construction, namely araldite AY103-1. The gain loss is concentrated upstream the gas flow, due to the beneficial effect of ozone produced under the source and transported downstream. The aging rate was reduced by longterm flushing and by the addition of a few percent of O_2 to the gas mixture. Finally, the LHCb Outer Tracker has not shown any sign of gain degradation over its lifetime within the LHCb detector between 2008 and 2018, presumably because of the intrinsic beneficial effects of ozone production in the entire volume of the Outer Tracker, overcompensating any malicious formation of insulating deposits. The cure of applying a large positive high voltage (beyond the amplification regime), to remove any insulating deposits, was not necessary. Given the excellent performance of the Outer Tracker until its last days of operation, potential re-use of the detector can be foreseen.

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