# Detailed Performance of the Outer Tracker at LHCb

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ABSTRACT: The LHCb Outer Tracker is a gaseous detector covering an area of $5 \times 6 \, \text{m}^2$ with 12 double layers of straw tubes. Based on data of the first LHC running period from 2010 to 2012, the performance in terms of the single hit resolution and efficiency are presented. Details on the ionization length and subtle effects regarding signal reflections and the subsequent time-walk correction are given.

The efficiency to detect a hit in the central half of the straw is estimated to be 99.2%, and the position resolution is determined to be approximately 200 $\mu$m, depending on the detailed implementation of the internal alignment of individual detector modules. The Outer Tracker received a dose in the hottest region corresponding to 0.12 C/cm, and no signs of gain deterioration or other ageing effects are observed.

KEYWORDS: Tracking detectors; Gaseous detectors.

# Contents

# 1. Introduction

The LHCb detector is a single arm spectrometer aimed at measuring bottom and charm decays produced at $pp$ collisions at the LHC. The momentum determination of charged particles is crucial for measuring the invariant mass of $B$ candidates with superior resolution in order to separate $B^0$ from $B_s^0$ decays, and to optimally suppress contamination from background in rare $B$ decays.

The momentum of charged particles is measured by accurately determining the trajectory with the Vertex Locator before the magnet, and tracking detectors behind the magnet. The tracking system behind the magnet consists of silicon strip detectors close to the beampipe, and a straw tube detector in the outer parts. The latter Outer Tracker (OT) is a gaseous detector covering an area of $5 \times 6\,m^2$ with 12 double layers of straw tubes and is shown in figure 1.

The performance of the readout electronics of the OT, and the single hit resolution and efficiency, is presented in Ref. [1], based on data of the first LHC running period from 2010 to 2012. Here, more details are given on the ionization length and on subtle effects regarding signal reflections and the subsequent time-walk correction. In addition, examples are shown of internal misalignments in individual detector modules, which can lead to improved single hit resolution of 180 $\mu$m when taken into account.



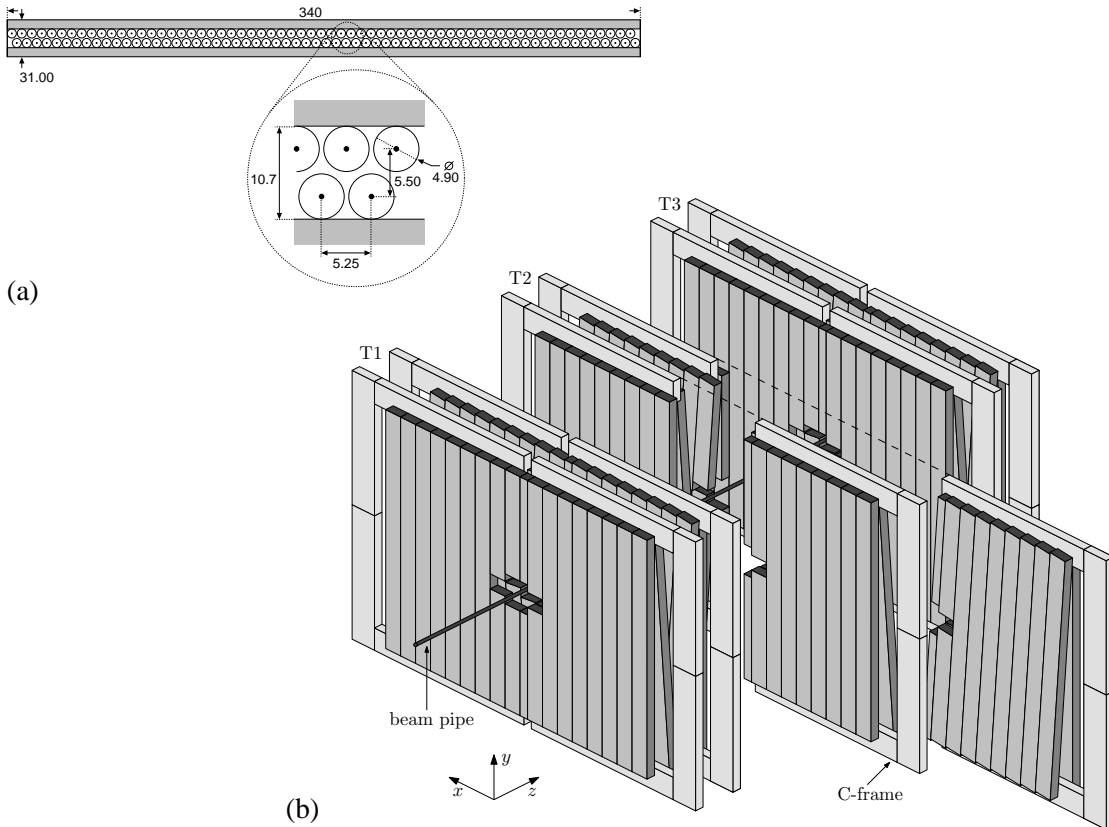**Figure 1.** (a) Module cross section. (b) Arrangement of OT straw-tube modules in layers and stations.

## 2. Detector operation

### 2.1 Gas monitoring

The counting gas for the straw tube detectors of the OT was originally chosen as an admixture of $Ar/CO_2/CF_4$. Studies on radiation resistance first suggested to operate without $CF_4$, and subsequently with the addition of $O_2$ [2], leading to the final mixture $Ar/CO_2/O_2$ (70/28.5/1.5). This choice is based on the requirement to achieve a reasonably fast charge collection to cope with the maximum bunch crossing rate of 40 MHz at the LHC, a good spatial resolution and to maximize the lifetime of the detectors.

The gas quality for the OT is crucial, as it directly affects the detector gain and stability, and potentially the hit efficiency and drift-time calibration. Moreover, a wrong gas mixture can lead to accelerated radiation damage or dangerously large currents. The gas gain is determined with the help of two custom built OT modules, of 1 m length, which are irradiated by a $^{55}$Fe source.

The measured pulse height is corrected for changes due to variations in the atmospheric pressure, and is shown in figure 2. The stability of the gas flowing into the OT detector ("input") and of the gas coming out of the OT ("output") are shown. The gas gain was typically stable within $\pm 10\%$ throughout the 2012 running period (when dedicated monitoring chambers were installed that were constructed with minimal contamination).
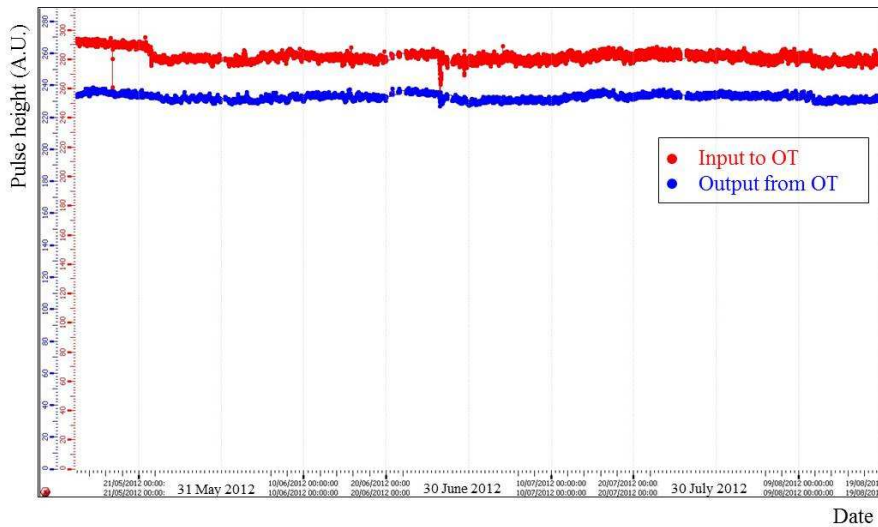


**Figure 2.** The gas quality of the OT is monitored by means of two dedicated monitoring chambers that measure the pulse height of $^{55}$Fe pulses. Both the input and output gas gain is stable over the period shown (Summer 2012).

## 2.2 Efficiency and occupancy

The LHCb experiment was designed to operate at an instantaneous luminosity of $2 \times 10^{32} \mathrm{cm}^{-2}\mathrm{s}^{-1}$ with 25 ns bunch spacing in the LHC. In the 2011 and 2012 running periods, the LHC machine was operating at 50 ns bunch spacing. The maximum drift-time in the OT straw cells is about 35 ns, and the measured times extend to about 50 ns due to variations in the propagation time, in time-of-flight, and small differences in time characteristics between individual front-end electronics boxes. The 50 ns bunch spacing of the LHC accelerator thus caused clear separation of observed OT hits originating from the different bunch crossings.

On the other hand, the LHCb detector managed to maintain its physics performance at double the design luminosity, between 3.5 and $4 \times 10^{32} \mathrm{cm}^{-2}\mathrm{s}^{-1}$, in 2011 and 2012, which effectively implies four times more overlapping interactions per bunch crossing than anticipated, leading to larger detector occupancies. On average about 7000 straws per event are hit (see figure 3a) corresponding to an occupancy of about 13%, of which about 2/3 are caused by particles created in secondary interactions, and about 1/3 are caused by particles coming from the primary interaction.

The probability that a charged particle leaves a hit when traversing the straw close to the wire ($r < 1.25$ mm) is about 99.2%. The small gap between two straws ($\sim 0.35$ mm) leads to an inefficiency of about 6.7%, and therefore typically 22 OT hits are expected for a charged particle traversing the entire OT detector, containing 24 monolayers (see figure 3c).

In addition, a small inefficiency is expected for charged particles traversing the edge of the straw. Due to the finite ionization length the probability to not ionize the gas increases close to the edge of the straw. The effective ionization length that is determined from the efficiency profile at the edge of the straw is about $(0.79 \pm 0.09)\mu$m. This is twice larger than theoretically expected, and is attributed to the probability that the signal from a single ionization cluster does not pass the amplifier threshold in the readout electronics, see also section 3.2.
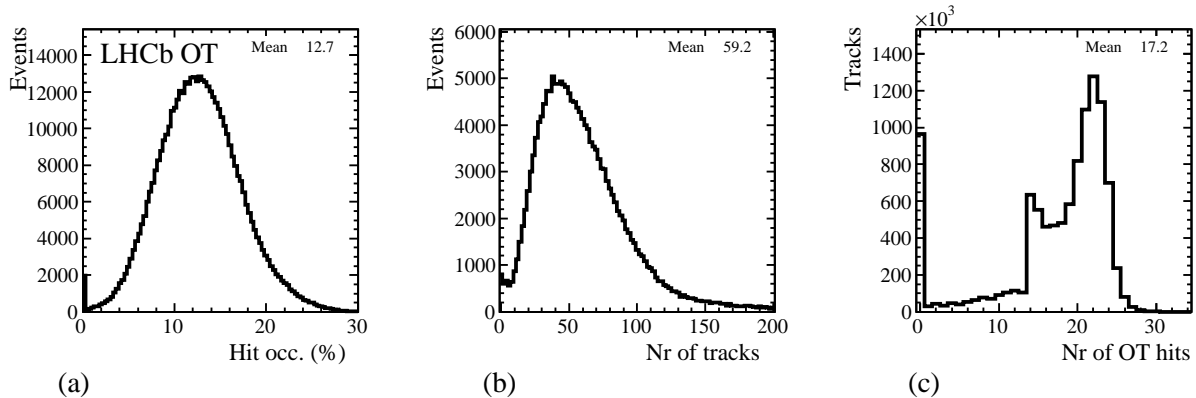


**Figure 3.** Typical run conditions for a run in June 2012 (run 118335), with (a) hit occupancies per event around 13% and (b) 60 tracks per event with hits in both the Vertex Locator and the tracking stations (so-called "long" tracks). (c) The number of OT hits assigned to these long tracks peaks around 22. A fraction of the tracks do not have any OT hits assigned, as these tracks only traverse the inner silicon detector at large rapidity close to the beampipe.

## 2.3 Bad channels

The hit efficiency is barely affected by malfunctioning channels in the detector or readout. With the full offline data set available, the performance of individual channels is monitored by comparing the occupancy to the expected value. First, the performance of entire groups of 32 channels is verified. Then, within a group of 32 channels, the occupancy is compared to the truncated mean, after correcting for the dependence of the occupancy on the distance to the beam. If the occupancy is above (below) 6 standard deviations from the truncated mean, the channel is declared "noisy" ("dead"). For a typical run recorded at the end of 2012 (run 133785), when all front-end modules were functioning properly, the OT contained 52 dead channels and 8 noisy channels, evenly distributed over the detector. The evolution of the number of bad channels throughout the 2011 and 2012 running periods is shown in figure 4. The three periods with larger number of dead channels correspond to a broken laser diode (VCSEL) between September and December 2011, a broken fuse in May 2012, and desynchronization problems between July and September 2012. Note that the front-end box at location M9 on the C-side reads out only 64 straws.
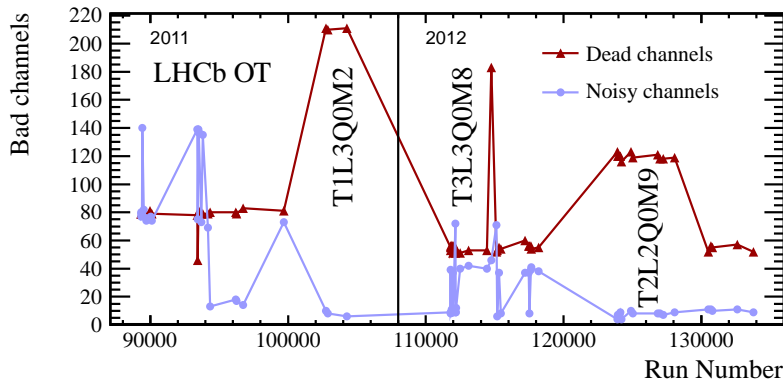


**Figure 4.** The evolution of number of dead and noisy channels as function of run number in the 2011 and 2012 running periods. The definition of dead and noisy channels is given in the text. The three periods with larger number of dead channels, correspond to periods with a problem affecting one entire front-end box (indicated in the figure).

## 3. Drift time

### 3.1 RT relation

The observed drift-time spectrum with the 50 ns bunch spacing of the LHC resembles closely the spectrum that is expected from a parabolic drift-time vs distance relation. Due to the fact that the clusters close to the wire drift faster than the clusters far from the wire, more hits are observed at small drift-times, compared to large drift-times.

The relation between the drift-time and the distance to the wire is determined [3] to be

$$t_{\text{drift}}(r) = 20.5\,\text{ns} \cdot \frac{|r|}{R} + 14.85\,\text{ns} \cdot \frac{r^2}{R^2}, \tag{3.1}$$

which is in agreement to the dependence determined in beam tests [4].

## 3.2 Drift time spectrum and ionization length

The drift-time spectrum for charged particles traversing the straw at small distances to the wire, $r < 0.1$ mm, is shown in figure 5. This distribution contains information on the effective ionization length. For small ionization lengths, the corresponding drift-time spectrum would peak sharply at small drift-times, because the clusters created close to the wire would be detected early. Alternatively, for large ionization lengths, the drift-time spectrum would extend to large drift-times, as the probability increases that no cluster is created close to the wire.

The ionization length that corresponds to the observed spectrum of figure 5 is about 0.7 mm, which agrees with the effective ionization length obtained from the drop in efficiency at the cell edge, see section 2.2. This shows that the effective ionization length is not affected by the drift distance, and that the clusters are not significantly absorbed on their drift-path towards the wire. Instead, the effective ionization length is presumably increased, with respect to expectations from the properties of the counting gas, due to the characteristics of the readout electronics.
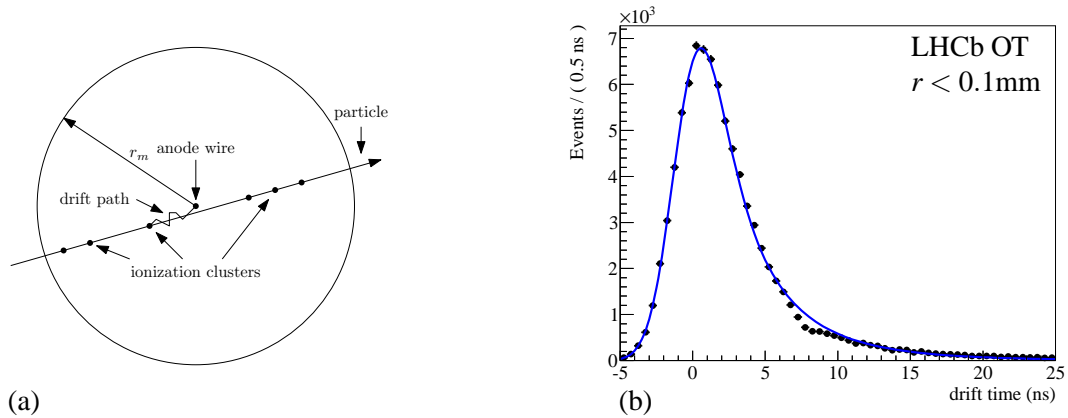


(a)　　　　　　　　　　　　　　　　　　　　(b)

**Figure 5.** (a) Charged particles that traverse the straw close to the wire ($r < 0.1$ mm) can be used to probe the ionization length. (b) The drift-time spectrum for particles traversing the straw close the wire peaks at low drift-times. (From Ref. [3].)

## 4. Hit resolution

The resolution with which the hit position is determined, affects the momentum determination and is a key parameter of the OT performance. Beam tests have shown that the combination of detector design and front-end electronics specifications locally lead to a hit resolution significantly better than the specified 200 $\mu$m [4]. Two subtle effects in the OT detector within the LHCb experiment globally affect the hit resolution and are described below.

### 4.1 Walk correction

The measured drift-time depends on the signal height. The larger the signal height, the faster the rise time, and thus the smaller the measured drift-time. This effect is known as "time-walk".

The wires are disconnected at the center of the detector, around $y = 0$ mm, and the channels are each readout at the top or bottom of the detector. The signals created by a traversing charged
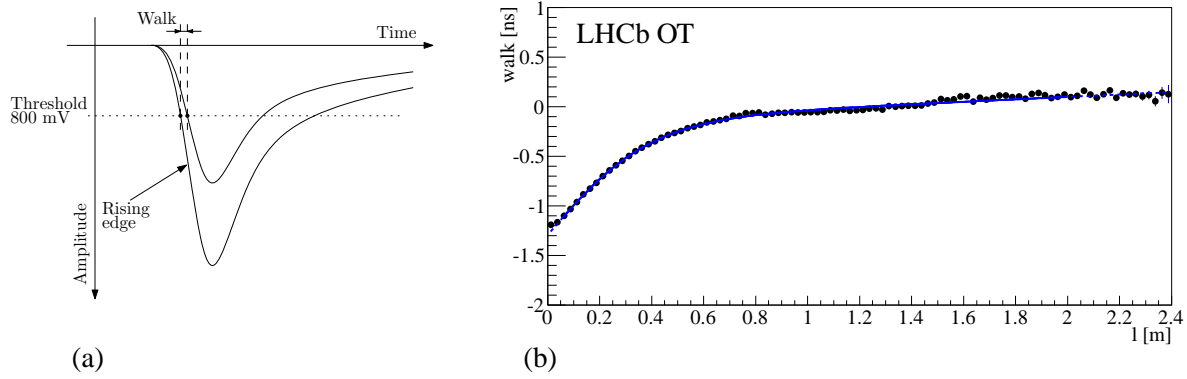
**Figure 6.** (a) The measured time depends on the signal height, and is generally referred to as time-walk. (b) The walk correction as a function of distance to the center. This correction accounts for hits with larger signal height close to the center of the detector, where the reflected signal adds to the original signal. (From Ref. [3].)

particle, propagate in both directions along the straw. The signal that travels towards the center of the detector will be reflected at the straw end. As a consequence, the hits close to the center of the detector will lead to a signal with almost twice the height of a signal far from the center, because both the two signals that originally traveled in opposite directions, will be close in time and thus overlayed. As a result, these hits will be systematically measured at earlier times than hits far from the center. The walk correction as function of distance to the center is shown in figure 6, and amounts to 1 ns at the center of the detector. This correction improves the overall resolution, given the intrinsic time resolution of 3 ns, and is included in the LHCb track reconstruction.

## 4.2 Monolayer shifts

A second feature that affects the resolution are any deformations of the detector module that are not accounted for in the offline alignment procedure. The number of degrees of freedom in the offline alignment procedure is limited to allow for smaller correlations and better convergence. The smallest OT element used in the alignment is half a detector module, which is allowed to rotate and translate within certain boundaries as determined from geometrical surveys in situ.

Recently it turned out that the mechanical deformations within individual detector modules are larger than anticipated, with excursions up to $\pm 0.4$ mm [3]. The main feature is that the two monolayers of straws within a single module are displaced transversely. Three examples of the transverse displacements of the 128 straws in one module as a function of the module length are shown in figure 7.

The overall hit resolution improves if the two monolayers within one detector module are allowed to be relatively displaced to each other in the alignment procedure. By allowing a different average horizontal displacement per half monolayer, containing 64 straws, a single hit resolution of approximately 180 $\mu$m is in reach. Also allowing for a rotation of each half monolayer, further improves the single hit resolution to 160 $\mu$m. These values refer to a Gaussian width of the resolution, determined from a fit to the residual distribution, within two standard deviations of the mean. This is in good agreement with the hit resolution below 200 $\mu$m, as obtained in beam tests [4].
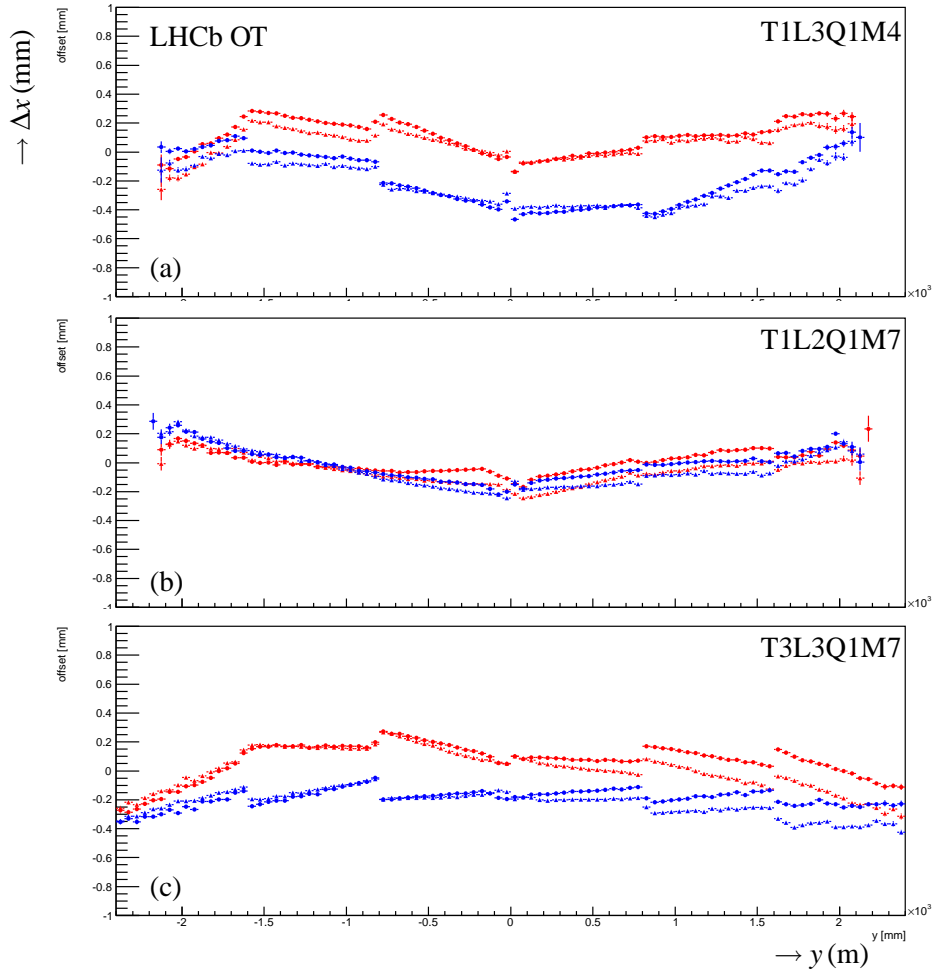
**Figure 7.** Average hit residual as function of the *y* coordinate in three modules (a) T1L3Q1M4, (b) T1L2Q1M7 and (c) T3L3Q1M7. The red symbols indicate the 64 straws of one monolayer, and blue symbols indicate the straws in the second monolayer. Wire locators are placed inside each straw every 80 cm along the wire, which affect the position of the wire. The observed pattern differs from module to module, but the 64 straws *within* one monolayer typically exhibit the same behaviour. In addition, the displacement of the straws vanishes for all 128 straws at the two extremes, where the position of the detector module is constrained by means of precision dowel pins.

## 5. Radiation hardness

It was discovered that, in contrast to the excellent results of extensive ageing tests in the R&D phase, final production modules suffered from gain loss after moderate irradiation (i.e. moderate collected charge per unit time) in laboratory conditions. The origin of the gain loss was traced to the formation of an insulating layer on the anode wire [2], that contains carbon and is caused by outgassing inside the gas volume of the plastifier di-isopropyl-naphthalene contained in the glue [5]. Remarkably, the gain loss was only observed upstream of the source position with respect to the gas flow. A negative correlation was observed between the ageing rate and the production of ozone [2], which suggests that the gain loss is prevented under and downstream of the source due

to the formation of ozone in the avalanche region. As a consequence it was decided to add 1.5% $O_2$ to the original gas mixture of $Ar/CO_2$, to mitigate possible gain loss. In addition, a beneficial effect from large induced currents was observed, which removed the insulating layers from irradiation in the laboratory. These large currents can either be invoked by large values of the high voltage in the discharge regime (dark currents), or by irradiating the detector with a radioactive source [5].

No signs of gain loss have been observed in the 2010 to 2012 data taking period of LHCb, corresponding to a total delivered luminosity of $3.5\,\mathrm{fb}^{-1}$. Most of the luminosity was recorded in 2011 and 2012, corresponding to about $10^7$ s of running at an average instantaneous luminosity of $3.5 \times 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, and the region closest to the beam accumulated an integrated dose equivalent to a collected charge of $0.12\,\mathrm{C/cm}$. Possible changes in the gain are studied by increasing the amplifier threshold value during LHC operation, and comparing the value where the hit efficiency drops. This value of the amplifier threshold can be converted to hit charge, which provides information on the change of the detector gain. This method to measure gain variations is outlined in detail in Ref. [6].

## 6. Conclusions

The LHCb Outer Tracker performed superbly during the 2010 to 2012 data taking period at the LHC. The number of noisy and dead channels was at the level of a few permille, and the hit efficiency (99.2%) and position resolution (better than $200\,\mu$m) were as expected from beam tests. Detailed studies of the effects of time-walk due to signal reflections, and internal misalignments of individual detector modules further improve the hit resolution for optimal track reconstruction. Dedicated studies of the effective ionization length show that single clusters are not absorbed on their drift path towards the wire. The intense radiation environment at the LHC, corresponding to a collected charge of $0.12\,\mathrm{C/cm}$ at the hottest spot of the Outer Tracker, did not show an effect on the signal gain.

## Acknowledgments

## References

[1] R. Arink et al., *Performance of the LHCb Outer Tracker*, `arXiv:1311.3893` [physics.ins-det].

[2] S. Bachmann *et al.*, *Ageing in the LHCb outer tracker: Phenomenon, culprit and effect of oxygen*, Nucl. Instrum. Meth. **A617** (2010) 202.

[3] A. Kozlinskiy, *Outer Tracker calibration and open charm production cross section measurement at LHCb*, PhD thesis, Vrije Universiteit, Amsterdam, 2013, CERN-THESIS-2012-338.

[4] G. van Apeldoorn *et al.*, *Beam tests of final modules and electronics of the LHCb outer tracker in 2005*, CERN-LHCB-2005-076.

[5] N. Tuning *et al.*, *Ageing in the LHCb outer tracker: Aromatic hydrocarbons and wire cleaning*, Nucl. Instrum. Meth. **A656** (2011) 45.

[6] D. van Eijk *et al.*, *Radiation hardness of the LHCb Outer Tracker*, Nucl. Instrum. Meth. **A685** (2012) 62.