LHCb Note 2002-031
May 13, 2002

Specifications for the drift gas quality of the outer tracking system

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Abstract

In this document we propose specifications about the gas quality required for a safe operation of the straw tube detectors in the outer tracking system. Consequences for the gas tightness of the detecting elements and the module boxes are discussed.

1 The outer tracking system

The outer tracker system of the LHCb experiment consists of a large number of straw tube detectors. It is subdivided in stations, each made up of 4 double layers of straw tubes. The double layers are arranged in an $x/u/v/x$-geometry, i.e. two layers (x-layers) are oriented with the wires vertical, while the u/v-layers are tilted with respect to the x-layers by $\pm 5^o$. The straw tubes are split in the middle, to limit the occupancy of individual straws in the experiment. 256 straw tubes are housed in one module with the two layers staggered. A view of 3 consecutive stations is shown in figure 1. The arrangement of the straws in a module is sketched in figure 2. The outer tracking system is described in detail in [1].

2 Gas distribution

This section describes the gas distribution to the detectors and the gas flow inside the modules.

2.1 Gas system for the outer tracker

The straw tubes will be operated using an $Ar/CO_2/CF_4$ (75/10/15) drift gas mixture. The whole detector volume will be exchanged every two hours. It is circulated in a closed loop system. The gas system consists of a mixing system, the distribution system, a pressure regulation and a purifier. Pressure regulation of the gas system insures the pressure and the safety bubbler insures that the pressure will not go above 2 mbar.

The gas is regenerated at a rate of about 90%. The inevitable requirement to limit the impurities in the straw tubes poses restrictions to the leak rate of the modules, as discussed in section 4. For more details on the outer tracker gas system see [1].

2.2 Gas flow

To understand the gas flow through the straw tube modules a short description of their composition is given. The length and the width of a module are about 5 m and 340 mm, respectively, its height is 33 mm. It is made of a gas tight box, housing 256 straws. The gas box consists of two sandwich panels, two end pieces and two lateral strips, joining the length of the module. The sandwich panels have a 10 mm core material made of honeycomb or Rohacel, with facings of 0.1 mm thick carbon fibre epoxy. 0.5 mm thick carbon fibre

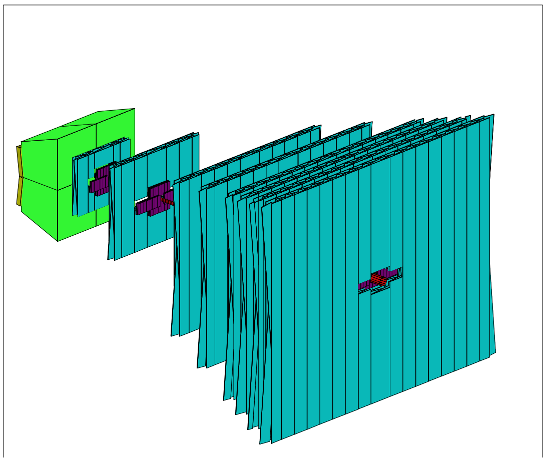

Figure 1: View of the stations of the outer tracking system.

or glass fibre epoxy is used for the lateral strips. Both, the sandwich panels and the lateral strips, are laminated with 15 μm thick aluminium, forming a Faraday cage around the detectors. A sketch of the module assembly is given in figure 2.

The end-pieces serve as gas distribution boxes. The gas is split in two independent lines, one supplying the straw tubes with counting gas, the second flushes the envelope volume of the modules.

Figure 3 illustrates the flow of the gas through the detector. The advantages of this gas flow scheme are:

- A protection of the counting gas against impurities entering the modules, provided the straw tubes are gas tight.
- The possibility to monitor the quality of the counting gas independent of the envelope gas as shown in figure 3.

3 Gas purity

Leakages in the detector boxes lead to an accumulation of oxygen, nitrogen and water vapour in the counting gas. These impurities may harm the detector mainly by four effects:

- Oxygen and nitrogen are strongly electronegative: Therefore electrons released in the detector may be captured before they reach the wire

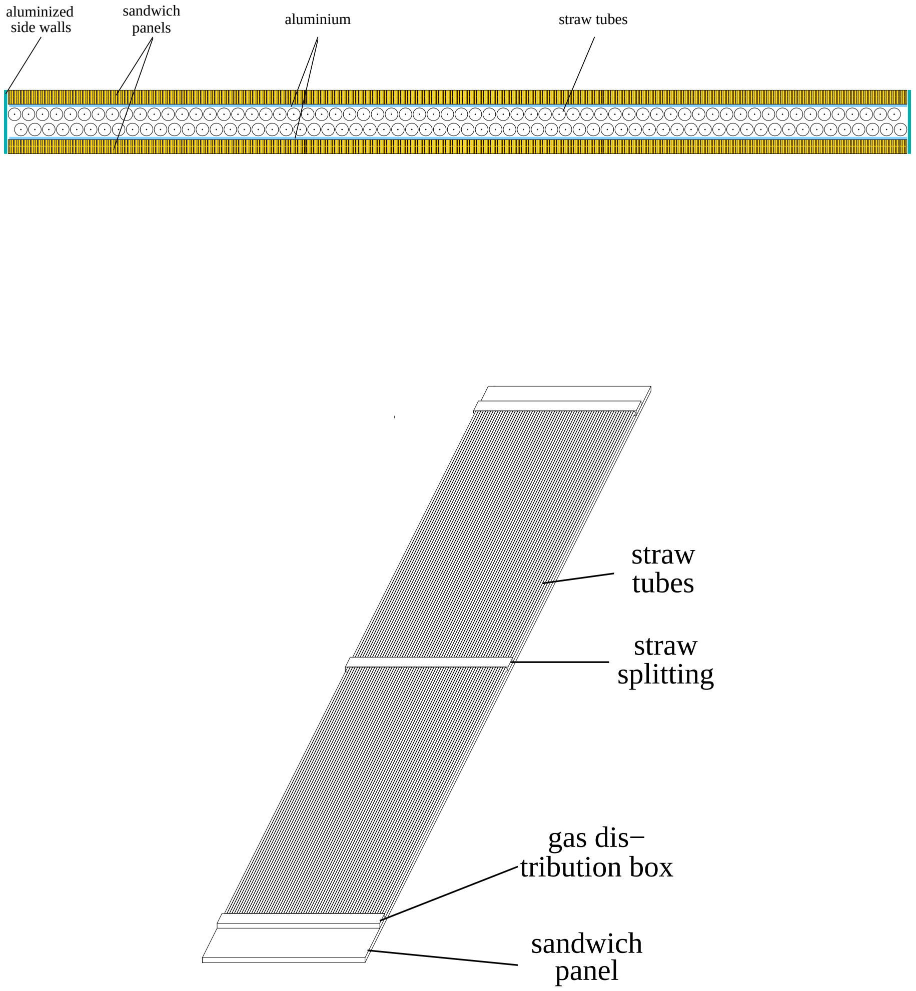

Figure 2: Assembly of the straw tube modules: Cross section through the module (top) and view of a half module including one straw tube layer. The second half is mirrored, giving a double layer of straw tubes for one module.

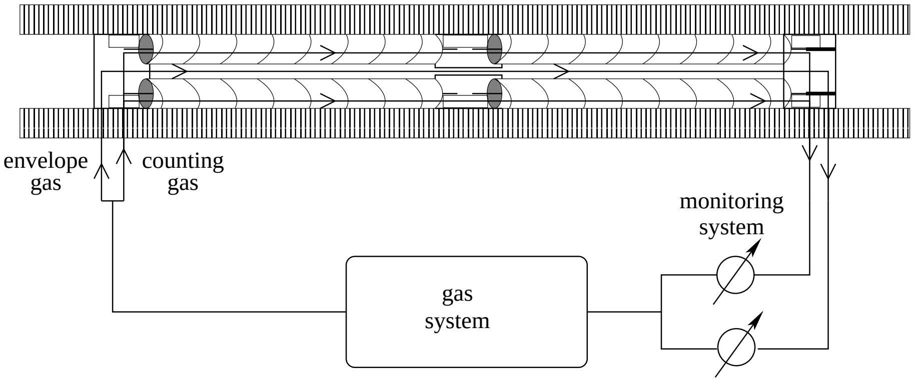

Figure 3: Gas flow through the straw tube modules

and gas amplification takes place. This results in a loss of efficiency and a decrease of the spatial resolution of the detector.

- Change of the space-time relation: Impurities influence the drift velocity of the electrons in an uncontrolled manner. This leads to a degradation of the spatial resolution of the detector.
- Change of gas gain: Impurities change the gas amplification factor. Therefore the efficiency and the spatial resolution is affected by the impurities.
- Possible acceleration of ageing: The knowledge about the influence of nitrogen, oxygen and water on ageing is not conclusive. But it is plausible that these impurities should be avoided in the counting gas, as radicals containing hydrogen, oxygen and fluor may be created in the gas amplification process, resulting in the formation of extremely reactive compounds.

The accumulation of oxygen and H_2O can be compensated by the purification in the gas circuit. Nitrogen, on the other hand, is difficult to remove once introduced to the gas. In the LHCb gas system the level of nitrogen contamination is limited by exchanging 10% of the counting gas when circulating the gas once.
The most dangerous effect is ageing! The rule to avoid ageing is to maintain a well known and controlled gas mixture. Any pollution, either coming from the environment or being produced intrinsically, e.g. by the use of outgasssing materials in the detector construction or the gas system itself, have to be kept on a level as low as possible.

The influence of the impurities on the space-time relation can be given quantitative by a simulation using the program GARFIELD [2]. Figure 4 shows the simulated drift velocity as a function of the electric field and the space-time relation in the straws for the preferred LHCb gas mixture $Ar/CO_2/CF_4$ (75/10/15). The relation is to a good approximation linear, the drift velocity for the electrons is $v_d = 83\ \mu$m. Figure 5 shows the deviation of the space-time relation in the presence of impurities. LHCb aims for a spatial resolution of 200 μm for the outer tracker system. To ensure that the impurities do not diminish the spatial resolution of the detectors substantially the error introduced should be below 100 μm. With the value of the drift velocity given above it is therefore reasonable to require that the drift time is not changed by more than 1 ns due to impurities. This requirement results in a maximum level of impurities of 2% for nitrogen and 0.5% for water. The limits obtained from these considerations are not tight. The reason is the short drift length in the straw tubes resulting in a small absolute change of the drift time is small. The limits given have to be used as upper limits for the allowed contamination, as other effects may degrade the detector performance more seriously.

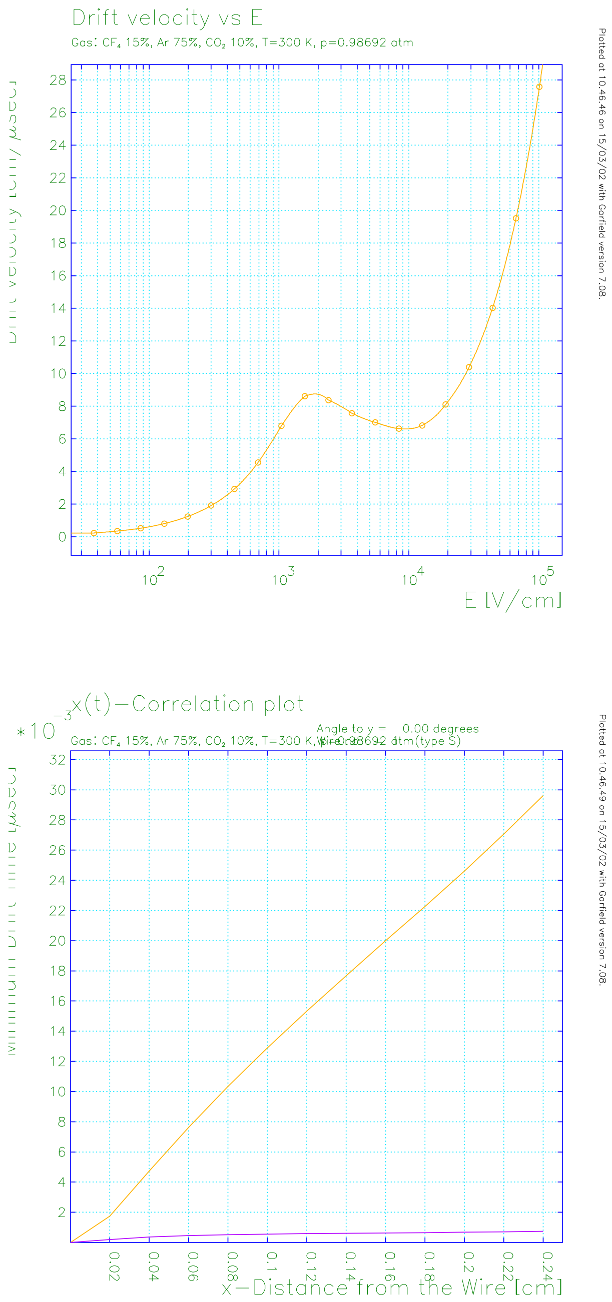

Figure 4: Drift velocity as a function of the electric field (top) and space time relation for the LHCb default gas, Ar/CO$_2$/CF$_4$ (75/10/15).

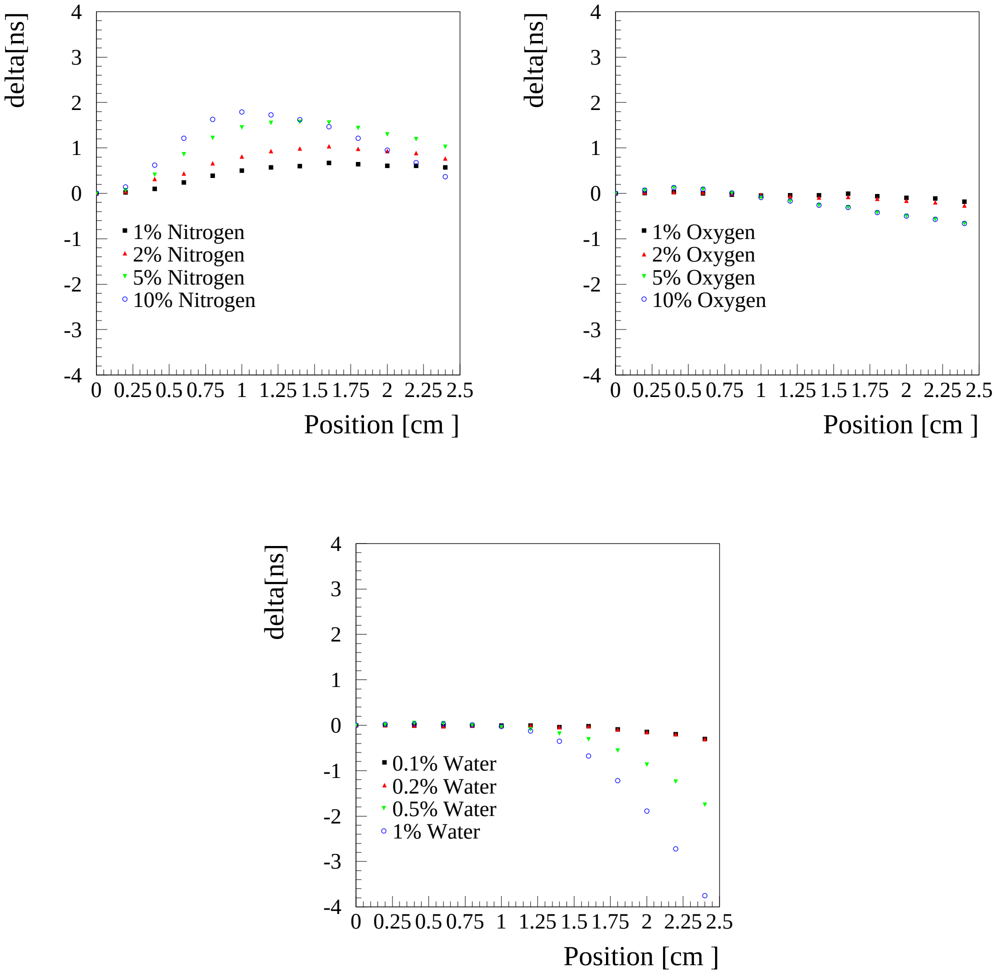

Figure 5: Deviations of the space time relation caused by impurities. Positive values indicate a shorter charge collection time for the contaminated gas. system.

4 Leak rate, permeability and diffusion

Impurities may enter the modules by two mechanism. First, it may permeate the walls by diffusion, second it may enter by diffusion through leaks. For the LHCb outer tracker modules the second effect dominates.

4.1 Leak rate and permeability

The presence of leaks in the walls of a volume obviously results in the observation, that the volume is not gas tight. To characterise gas leaks often the leak rate of a volume is given. It is measured by applying an overpressure Δp_0 to the volume, and measuring the decay rate of the overpressure $\frac{\Delta p}{\Delta t}$. If the measurement is performed at a total pressure of p, the leak rate is given by

$$R = \frac{\Delta p}{p \cdot \Delta t}. \tag{1}$$

Figure 6 shows a typical set-up for the measurement of the leak rate. The extra volume includes the volume of gas pipes. To increase the time constant and therefore the precision of the measurement especially for small test volumes, an additional gas volume might be added to the set-up.

The definition of the leak rate given in equation 1 introduces a dependency of the measured leak rate from the parameters in the set-up: If the extra volume is increased, the leak rate decreases. For a high initial overpressure a higher leak rate will be measured compared to a low initial overpressure. The measured leak rate depends also on the geometry of the object under test. It scales with the ratio A/V, where A denotes the surface and V the volume of the object.

To avoid the dependency on the specific parameters chosen for the measurement it is better to refer to the permeability of the test volume. The permeability P is defined as the gas volume ΔV permeating a surface of the area A during a time period Δt, at a pressure difference Δp_0 between both sides of the surface:

$$P = \frac{\Delta V}{A\, \Delta p_0\, \Delta t}. \tag{2}$$

Using

$$\frac{\Delta p}{p} = \frac{\Delta V}{V} \tag{3}$$

the permeability is related to the leak rate by

$$P = \frac{V}{A\, \Delta p_0} R \tag{4}$$

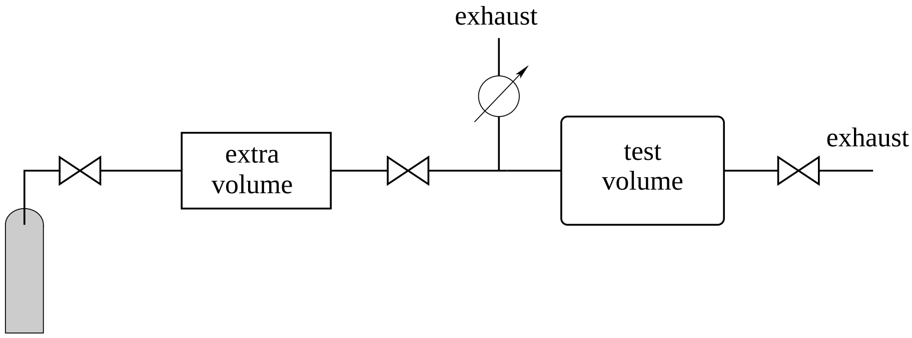

Figure 6: Set-up to measure leak rates of straw tubes.

V denotes the total gas volume in the experimental set-up. The factor V/A cancels the dependence on the geometry of the object mentioned above. Using equation 4 it is possible to quantify the gas tightness of an object by the measurement of the leak rate, but independent of the specific parameters of the experimental set-up.

4.2 Back diffusion

The main source of impurities in the gas of the outer tracker system will be due to back diffusion through leaks in the walls of the gas box. To get a quantitative idea of this effect consider a volume V limited by walls of thickness Δx. The volume is filled with a gas species labelled X, while the surrounding gas species is labelled Y. Assume a hole of size S in the wall connecting the volume to the surrounding environment. According to Fick's first law the mass transport into the volume is given by:

$$\frac{\Delta m_Y}{\Delta t} = D\,S\,\frac{\Delta \rho_Y}{\Delta x}. \tag{5}$$

Using the molecular weight M_Y, the number of molecules diffusing into the volume can be written as

$$\Delta n_Y = \frac{\Delta m_Y}{M_Y}. \tag{6}$$

Therefore

$$\Delta n_Y = \frac{D\,S}{M_Y}\,\frac{\Delta \rho_Y}{\Delta x}\,\Delta t. \tag{7}$$

To get the relative level of impurities after a time Δt, Δn_Y has to be divided by the total number of molecules inside the volume:

$$n_X = \frac{\rho_X \cdot V}{M_X}. \tag{8}$$

This yields

$$\frac{\Delta n_Y}{n_X} = \frac{D\,S}{\rho_X\,V}\,\frac{M_X}{M_Y}\,\frac{\Delta\rho_Y}{\Delta x}\Delta t \tag{9}$$

4.3 Application to module boxes

The minimum requirement for the outer tracker modules is a gas loss rate not exceeding the amount of gas added to the system, i.e. the gas lost per volume exchange must not exceed 10% of the total gas volume. For the geometry described in section 2.2 the volume of one box is 54.4 l, therefore the maximum amount of gas lost during one gas exchange, i.e. within two hours, is about 5 l. Assuming an overpressure in the boxes of 1 mbar, this corresponds to a leak rate of

$$R_{\mathrm{max}} = 1.4 \cdot 10^{-5}\,\mathrm{s}^{-1} \tag{10}$$

converting into a permeability of

$$P_{\mathrm{max}} = 2 \cdot 10^{-4}\,\frac{\mathrm{m}}{\mathrm{bar\ s}}. \tag{11}$$

It is instructive to calculate the level of impurities expected for modules operated in the LHCb outer tracker system, if their gas tightness full-fills the minimum requirement on gas tightness given above. For that, it is assumed that the leak is caused by a single hole of radius r in the 0.5 mm thick side walls of the box described in section 2.2. According to the law of Hagen-Poiseuille for a laminar gas flow the flux through the leak is given by

$$\dot{V} = \frac{\pi\Delta p_0}{8\eta l}r^4. \tag{12}$$

Δp_0 is the overpressure applied, η the viscosity of the gas and l the thickness of the side wall. Using equations 1, 3 and 4 the radius of the hole is given by

$$r = \left(\frac{8\eta l A P}{\pi}\right)^{\frac{1}{4}} \tag{13}$$

Using the viscosity for Argon ($\eta = 22,5 \cdot 10^{-11}$ bar s) and $P = 2 \cdot 10^{-4}\mathrm{m\ bar}^{-1}\mathrm{s}^{-1}$ the radius of the hole is $r = 120\ \mu$m. For a hole of that size the level of impurities expected can be determined from equation 9. To simplify matter it is assumed that the module is filled with pure Argon and it is surrounded by a Nitrogen atmosphere. The diffusion constant D for Nitrogen in Argon is $0.17\frac{cm^2}{s}$ [3]. As nitrogen can not be removed from the gas by purification it is only removed by the exchange of the gas. The whole gas volume is exchanged once every 20 hours, therefore Δt is assumed to be 72.000 s. Using these assumptions equation 9 yields

$$\begin{aligned}
\frac{\Delta n_{N_2}}{n_{Ar}} &= \frac{D\,S}{\rho_X\,V}\,\frac{M_X}{M_Y}\,\frac{\Delta\rho_Y}{\Delta x}\Delta t && (14)\\
&= \frac{0.17\frac{\mathrm{cm}^2}{\mathrm{s}}\,\pi\,(1.2\,10^{-4}\mathrm{m})^2}{1.410^{-3}\,\frac{\mathrm{g}}{\mathrm{cm}^3}\,0.544\,\mathrm{m}^3}\,\frac{40\frac{\mathrm{g}}{\mathrm{mol}}}{28\frac{\mathrm{g}}{\mathrm{mol}}}\,\frac{0.8\,10^{-3}\frac{\mathrm{g}}{\mathrm{cm}^3}}{0.05\,\mathrm{cm}}72.000\,\mathrm{s} && (15)\\
&= 1380\ \mathrm{ppm}. && (16)
\end{aligned}$$

It is important to stress that the relation between the leak rate and the level of contamination is not unique. The example described is even the most optimistic. For example the leak rate is unchanged for 100 leaks of only 12 μm radius, but as the total area of leaks is increased by a factor of 10, a contamination level 10 times higher compared to equation 16, i.e. 1.38% is expected. This level is already critical as discussed in section 3.

The separation of the counting gas flow and the envelope gas flow used does not protect the straws against nitrogen contamination, as the counting gas and envelope gas are mixed in the closed loop of the gas system.

To account for these effects we propose a maximum permeability of

$$P_{\mathrm{max}} = 2 \cdot 10^{-5}\,\frac{\mathrm{m}}{\mathrm{bar\,s}}. \tag{17}$$

as specification for the gas tightness of the modules.

4.4 Specification for straw tube gas tightness

Assuming a gas tight module box according to the specification given in the preceeding section the requirements for the gas tightness of the straw tubes come mainly from the necessity to separate both gas volumes to reach a controlled gas flow through the module. A reasonable assumption is that this condition is fulfilled, if not more than 5% of the straw tube volume is lost to the envelope volume during one gas exchange, i.e. during two hours. From equation 4 it can be derived that a permeability of

$$P = \frac{V}{A}\,\frac{1}{\Delta p_0\,\Delta t}\,\frac{\Delta V}{V} \tag{18}$$

is allowed. If the volume loss is restricted to $\frac{\Delta V}{V} = 0.05$ during a time period of $\Delta t = 7200$ s this converts into a permeability of

$$P = 8.7 \cdot 10^{-6}\,\frac{\mathrm{m}}{\mathrm{bar\,s}}. \tag{19}$$

Including some safety margin we propose a maximum allowed permeability of the straw tubes of

$$P = 1 \cdot 10^{-6} \, \frac{\mathrm{m}}{\mathrm{bar\,s}}. \tag{20}$$

To reach this permeability for the straw tubes is technological feasible.

5 Summary of specifications

To guarantee a reliable operation of the outer tracking system in the LHCb experiment it is inevitable to maintain the level of impurities entering the counting gas at a low level. The main reasons for this are changes of the operation point of the straw tubes and possible degradation of the detector performance, e.g. by ageing effects, induced by impurities. The gas tightness of both, the module boxes and the straw tubes, is mandatory to avoid these undesired effects. As specification for the gas tightness of these elements we propose a maximum allowed permeability for these elements:

$$\begin{aligned} \text{For the modules:}\quad P &= 2 \cdot 10^{-5} \, \frac{\mathrm{m}}{\mathrm{bar\ s}} \\ \text{For the straw tubes:}\quad P &= 1 \cdot 10^{-6} \, \frac{\mathrm{m}}{\mathrm{bar\ s}} \end{aligned}$$

In addition to this it is advised to control the gas quality obtained under realistic gas flow condition by means of e.g. measuring the concentration of water.

References

[1] LHCb outer tracker, Technical Design Report

[2] R.Venhof, *GARFIELD*, A drift chamber simulation program, CERN PRogram Library 1998

[3] D'ans, Lax; Taschenbuch für Chemiker und Physiker, Vol. 1, Springer–Verlag Berlin · Heidelberg, 1967