Methods used for Gas Tightness Test and percent Oxygen Monitoring of the NSW Micromegas Detectors of LHC-ATLAS Experiment

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Abstract. In the frame of the LHC-ATLAS Upgrade of phase I, the New Small Wheel detector system is under integration and commissioning at CERN Laboratories. One of the detector type, the Micromegas detectors, during their integration are tested in several stages for gas tightness validation. In particular, the novel method we are using for the gas tightness test, that we called "Flow Rate Loss", has been realized in several semi-automatic fixed, portable and stand-alone setups for testing either the Micromegas Quads or the final Double Wedges. The obtained measurements up-to-date are presented as well as their obtained statistical distribution. Additionally, during the performance evaluation of the detectors, a percent oxygen monitoring is also performed in 24-hour base. The methods and techniques we developed and used are presented analytically in this work.

1. Introduction

In the framework of ATLAS experiment upgrade at CERN [1], a new detector system, the New Small Wheel (NSW), is in the integration and commissioning phase. The NSW gas detectors use two kind of technologies, one primarily devoted to the Level-1 trigger function, "small-strip Thin Gap Chambers" (sTGC), and one for performing precision tracking, "Micromegas" (MM) detectors [2]. The MM detectors have outstanding precision tracking capabilities [3].

The NSW detector system is under integration and commissioning at CERN Laboratories at Building 899 (BB5) and 191 respectively. The MM detectors, during their integration pass several quality tests while the gas tightness validation is the first one after receiving the Quads for the constructions sides. Beside this test, during their performance evaluation in the Cosmic Ray Stand, percent oxygen monitoring and analysis is also performed. The methods and techniques that have been developed and used for the aforementioned requirements are presented in this work. In particular, the novel method for the gas tightness test, called "Flow Rate Loss" (FRL), has been realized in several semi-automatic fixed, portable and stand-alone setups for testing either the individual Micromegas Quads/Modules or the corresponding Double Wedges. The first stage gas tightness test is performed to a newly receiving MM Quads of Large or Small type by a fixed setup designed for testing four Quads at the same time. Appropriate software based on WinCC-OA platform [4] was developed for recording and analyzing the data. The subsequent stages of gas tightness test are performed exclusively by portable setups to the integrated MM Wedges before their overall validated phase as well as when are installed on both NSW.

For the percent oxygen study, a monitoring method and a setup based on a low cost Oxygen Probe Analyzer (OPA) with very low full scale, 0-1% was performed. The method we used provides very high precision of percent oxygen of the order of 10^{-3}. By this setup the percent oxygen during the regular gas flow of the detectors in NSW, in GIF++ area and in Cosmic Ray Stand at BB5 was monitored. The measurements can be performed either in Transient State Flow signal mode (TSF) or in Steady State Flow signal mode (SSF).

2. The baseline method for gas leak validation

The baseline method we have applied for the MM Quads and Wedges gas tightness validation was the FRL method. This method has been introduced since 2015 during the design of the gas system of NSW Micromegas. Its operation principle is based on mass concentration along a gas line where an additional branch (the leak branch) is included. In this branch we should have the flow rate which is equal to the leak rate of the volume under study. The equation describing the mass concentration in the three branches is given below

$$\begin{aligned} \dot{m}_1 = \dot{m}_2 + \dot{m}_L \Rightarrow \rho Q_1 = \rho Q_2 + \rho_o Q_L \Rightarrow \\ Q_{\mathrm{L}} = \frac{\rho}{\rho_o}(Q_1 - Q_2) = Q_{1,o} - Q_{2,o} = c\Delta V_{\mathrm{L}}^{net}[\mathrm{mL/h}] \end{aligned} \quad (1)$$

where $\Delta V_{\mathrm{L}}^{net}$ is the differential voltage output of two mass flow sensors in units [mL/h] (see in the next sections), $c \approx 3.4\ \mathrm{mL} \cdot \mathrm{h}^{-1} \cdot \mathrm{mV}^{-1}$ at NC:25°C, $P = 1.013$ bar, $\dot{m}_1, \dot{m}_1$ and $\dot{m}_L$ are the mass rates of gas in the input and in the leak branch respectively, ρ and ρ_o the gas densities in the instrument location and in the volume location under study respectively and Q_1, Q_2 and Q_{L} the flow rates in the input, output and leak branch respectively. This method, against the classical Pressure Drop Rate (PDR) has some significant advantages as follows:

(i) Is insensitive to the expansion or compression of the volume under test because the static pressure is maintained constant. This is very important in case of MM Quads or Wedges because they appear a quantitative volume change when a small overpressure is applied, even of the scale of a few [mbar].
(ii) It is insensitive to the temperature variation during a gas leak test.
(iii) The measured quantity is a constant value and not a rate. This allows for performing statistical analysis avoiding the use of fitting models, as in the case of PDR.
(iv) It allows monitoring of the leak rate during interventions for improving the tightness of the volume under study.
(v) The statistical uncertainty depends on the repeatability of the Mass Flow Sensors, and can be up to 0.2%, while it can be reduced by extending the lasting time.

Based on these advantages this method was the most appropriate for the gas tightness validation of the NSW Micromegas detectors. In the Laboratory BB5 at CERN we have installed a setup testing in parallel four Quads and two portable setups used in BB5 as well as for the NSW commissioning at Building 191.

2.1. Design of a stand-alone instruments

The original design concept that we had in mind was a device with the feature to cover the basic functions that we need in all the stages of integration and commissioning of the MM Quads and Wedges. In particular, for the flow rate measurement we used a principle of operation based on the Poiseuille's law applied to a small hollow tube that we call "impedance". This technique has been already used in the design of a stand-alone dual function digital flow meter - differential manometer in NTUA [5]. The appropriate impedances are of the type ZTM (DPS in Fig. 1), one for the input and one for the output. The flow rate - pressure relationship curve is obtained by calibration. For measuring the gauge pressure we used two differential pressure sensors with two different full scales, one for the Quads and Wedges gas leak test and one for the "spacer frame" test. For the pressure regulation we used a pressure regulator for higher pressures and an impedance for the lower pressures.

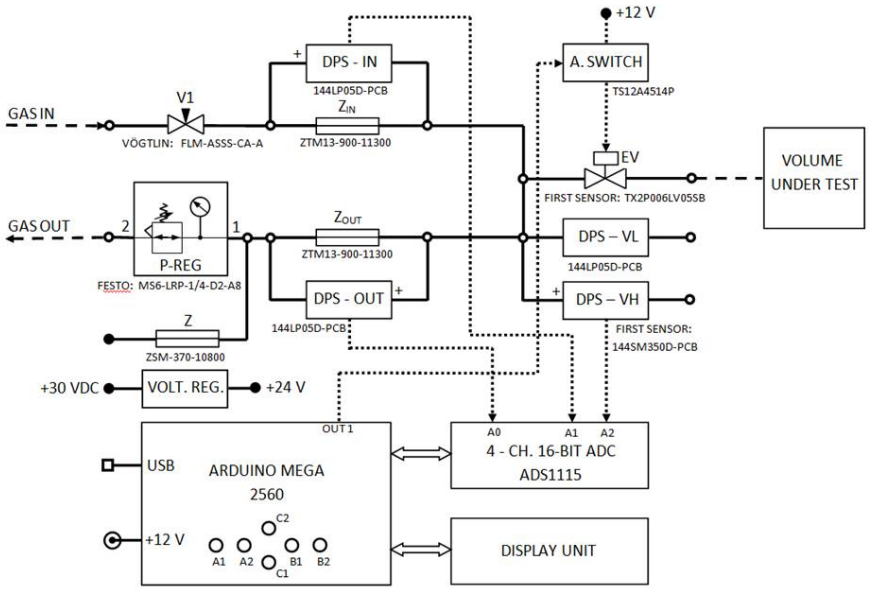

Figure 1. The electric-pneumatic drawing in building blocks of the SA-GLT. DPS-IN: Differential Pressure Sensor (F.S. 0-5 mbar), DPS-OUT: Differential Pressure Sensor (F.S. 0-5 mbar), DPS-VL: Differential Pressure Sensor (F.S. 0-5 mbar), DPS-VH: Differential Pressure Sensor (F.S. 0-350 mbar), P-REG: Pressure Regulator, EV: Electrovalve normal closed, V1: Flow Control Valve, ZIN: Gas impedance for upstream flow, Zout: Gas impedance for downstream flow.

Based on this original design constructed at CERN a prototype, that we call "Stand-Alone Gas Leak Tester" (SA-GLT). Afterwards, a second and similar one has been assembled having therefore, the SA-GLT-1 and SA-GLT-2. The constructed prototype had some small modifications according to the availability of the components. For the flow rate measurements we used two commercial Mass Flow Sensors (MFS) having very low full scale (0-6 L/h) for achieving the best absolute accuracy. The pressure regulator, the pressure sensor with higher full scale and the electrovalve [6] have not been used yet. This prototype incorporates all the acquired knowledge and experience on the FRL method, not only in the choice of the components but also in the monitoring software code. As a stand-alone device, it is equipped with a single 2x16 LCD screen for displaying all the monitored quantities, that is, the flow rate in the input branch, the flow rate in the output branch, the difference of the flow rates (that is the differential flow rate) and the gauge pressure in the volume under study. Moreover, it provides safety warning messages, instructions and elapse time. This multi-function capability is performed by an Arduino Mega 2560 micro-controller in conjunction with a 16-bit, 4-channels ADC card. The LCD screen is combined with a key-pad electronic card providing 6 keys (buttons) which are used for selecting a function. The electro-pneumatic structure is presented in Fig. 2. The front face with instructions of configuration of these keys is shown in Fig. 3. For the pressure regulation we use one or more "impedances" of the type ZTM.

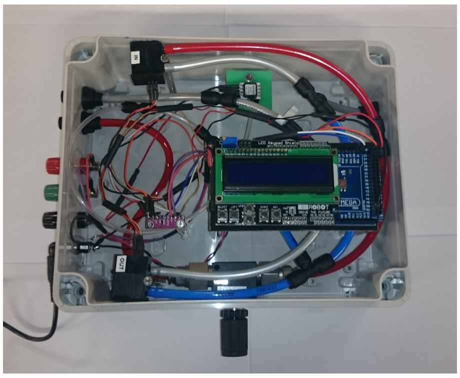

Figure 2. A photo of the internal structure of the SA-GLT prototype. Two commercial mass flow sensors (black small boxes at the up and down sides) are used in this version.

Figure 3. A photo of the front view of the SA-GLT prototype showing the LCD screen and the associated keypad.

2.2. Monitoring software and specifications

The Arduino language is based on the Wiring language, a variant of C/C++ for AVR architecture micro-controllers such as ATmega, and supports all basic structures of C as well as some features of C++. As for compiler, AVR gcc is used while AVR libc is used as the basic C library. In the prototype we have used an Arduino Mega 2560. The code includes a setup part for initialization and then it enters to a infinite loop checking the 6 keys of the LCD keypad. By pressing any key, the corresponding reading is performed. When another key is pressed, the new particular function starts. An overall flow chart of the code is presented in Fig. 4.

The flow rate in the input and output is recorded by Mass Flow Sensors (MFS), from OMRON, have an absolute accuracy of 5% and repeatability of 0.5% at full scale. However, operating at low fractions of full scale the repeatability goes down to 0.2%. When calculating the difference of the flow rates in the input and output the accuracy is increased to 7%. The gauge pressure is recorded by a differential miniature amplified low pressure sensor (144LP05D-PCB from First Sensor or HCLA series from PRO, type HCLA12X5U) with a full scale of 5 mbar and 12 mbar respectively. The accuracy of these sensors reading is at the scale of 0.1% based on the linearity given by the manufacturer. In addition, we used a number of readings in each measurement. In particular, for the flow rate and pressure we used 16 readings taking their mean value, while for the differential measurement of the leak rate we are using 4 readings taking the mean value in a loop, therefore, the fluctuations of the difference is suppressed by a factor of 2. The mean value is calculated inside the reading loop by using a recursive formula. Because of the 15 bits for the conversion of the ADC (one bit is used for the sign) the number of displayable digits are 4 2/3.

The software code includes some useful safety warnings and instruction messages, as it is described below:

- Warning "OVERPRESSURE": when the gauge pressure exceeds a safe limit for the detectors, that is, $p > 6$ mbar

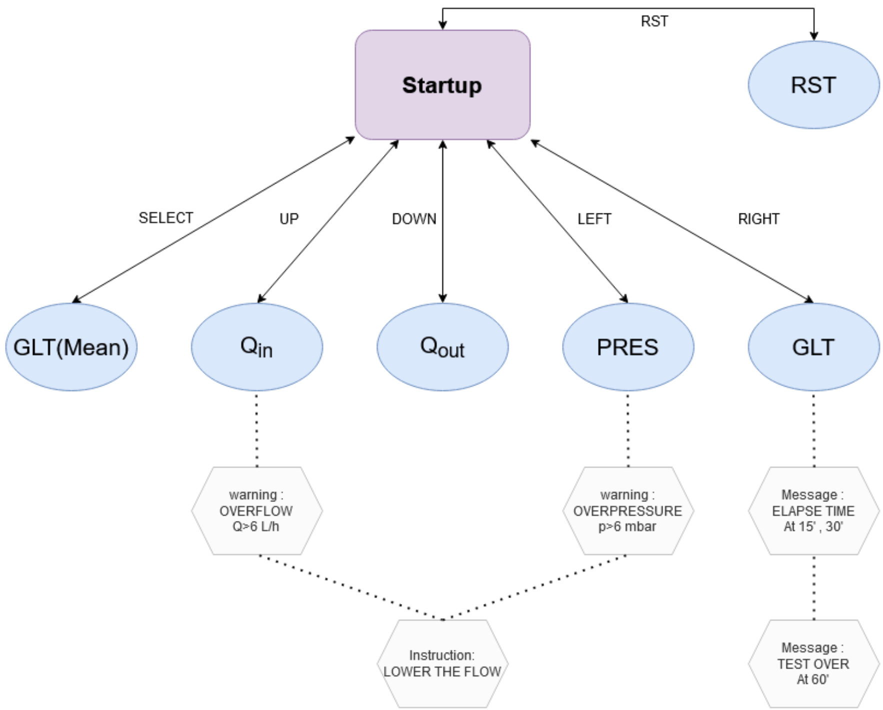

Figure 4. An overall flow chart of the software code used in the SA-GLT prototype.

- Warning "OVERFLOW": when the gas flow rate exceeds the full scale of the input MFS, that is, $Q > 6$ L/h
- Instruction "LOWER THE FLOW !": is given in cases of overpressure and overflow
- Message "ELAPSE TIME": is given at 15 min and 30 min from starting the gas leak test
- Message "TEST OVER": is given after 240 min which is the typical time duration of the gas leak test

3. Gas tightness validation stages

During the integration of the NSW at CERN, a number of validation tests are performed. A crucial quality test is that of gas leak tightness. This test, is performed in three stages of the detector integration and commissioning. In the stage-0 we tested the spacer frames of the detectors by using a portable setup equipped with Arduino Mega 2560 and 16-bit monitoring controlled by a WinCC-OA software interface [7] at much higher pressure, of the order of 140 mbar, for achieving higher accuracy. The stage-1 concerns the newly receiving MM Quads by using a system consisting by 4 Nodes (4 testing branches) installed at BB5, as shown in Fig. 5. The complexity of the experimental gas tightness validation requires the creation of an automated control system [8] based on WinCC-OA that enables the processing, control, and recording of data collected by the sensors. The data analysis was done either by quick histograms or via an advanced fitting procedure, as shown in Fig.6. This interface panel correspond to the test of Quad LM2-M38 which presented a leak rate of $Q_{\rm L}$=40.3 ±0.5 (stat.)±2(syst.) mL/h. We must notice that the obtained results, for practical reasons, normalize to the corresponding acceptance limit, that we call ATLAS limit symbolizing it by "A.L.". Thus, the previous result expressed in ATLAS limit is ×1.10 A.L. The "distance" of the mean of the two Gaussian distributions, in leak rate units, represent the net leak rate result which then is normalized to the nominal static pressure of 3 mbar.

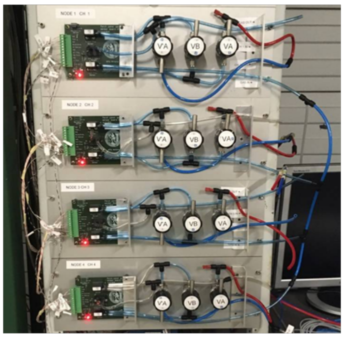

Figure 5. A photo of the 4-nodes setup for testing 4 MM Quads in parallel by FRL method.

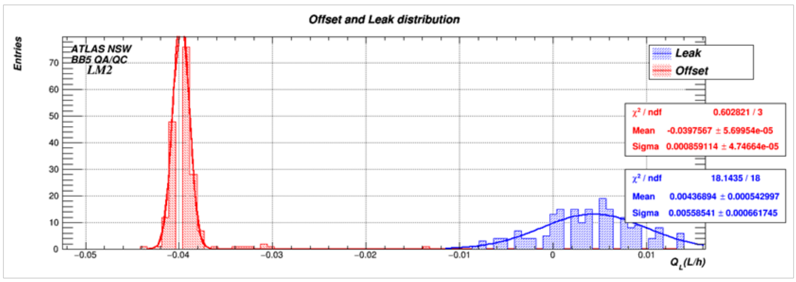

Figure 6. Advanced data analysis panel referring to the gas tightness test of the Quad LM2-M38. The blue histogram concerns the leak data and the red one the offset data of the two mass flow sensors. Both are fitted by Gaussian functions.

The stage-2 concerns an overall gas tightness validation performed to the completed double wedges (including the Quad pairs (LM1, LM2 and SM1, SM2) and both sides, IP and HO, by using two similar SA-GLT instruments at the same time. In stage-3 (using two portable setups) is performed to the Wedges when they have been installed on the NSW JD frame where the commissioning is done (at Building 191 at CERN). In all aforementioned tests the novel method FRL was used.

4. Obtained results and parametrization

As part of the quality control during the integration of the MM Quads in the Lab BB5 at CERN, 136 Quads in total were tested by means of their gas tightness performance using air from a bottle. The measured quantity was the leak rate (Q_{L}) in [mL/h] normalized at static pressure 3 mbar and converted to the nominal gas Ar+7%CO_2 according to literature. The lasting time of the test was 45-60 min, depending on the convergence of the differential signal in FRL method. Some minor problems in the gas fittings for the test were found and faced. A few Quads presented an increased internal leakage and were sent back to the construction sites for repairing. The acceptance limit of the leak rate that we used in this tests was specified as a fraction of the volume of the detector under study per unit time, that is, $10^{-5}/V$ per minute or $6 \times 10^{-4}/V$ per hour, where V is the detector volume. Thus, the individual acceptance limits were calculated as: for SM1 23.3 mL/h, for SM2 25.9 mL/h, for LM1 38.2 mL/h and for LM2 37.0 mL/h.

After finishing the gas tightness validation we have summarized the obtained data of the gas leak rate as well as their normalized value with respect to the ATLAS limit. The mean is 58.3 mL/h (x1.96 A.L.) and the rms is 69.9 mL/h (x2.04 A.L.). As we can see in Fig. 7, the most of the Quads gave leak rate values within the allowed range specified at 2-rms deviation. Only one Quad can be considered as outlier but it is expected adequate operation performance in its final position merged in a wedge. In Fig. 8 and Fig. 9 the overall statistical distribution and the associated histogram of the residuals are presented respectively.

The overall statistical distribution has been parametrized by using Gamma distribution which is a di-parametric distribution. Its parameters have been determined or "tuned" by using the obtained mean and rms value and found $a = 0.923$ (shape parameter) and $b = 2.123$ (scale parameter) respectively. The Gamma distribution is the "maximum entropy probability distribution" with minimum information (if nothing is known about the distribution under

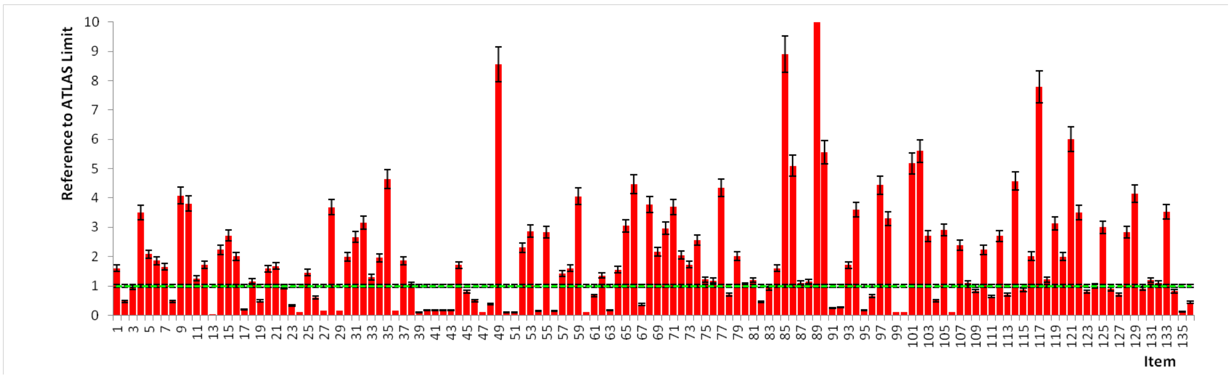

Figure 7. The histogram of the overall leak rate results, with respect to the ATLAS Limit (green horizontal dashed line), of 136 MM Quads during their gas tightness validation since January 2019.

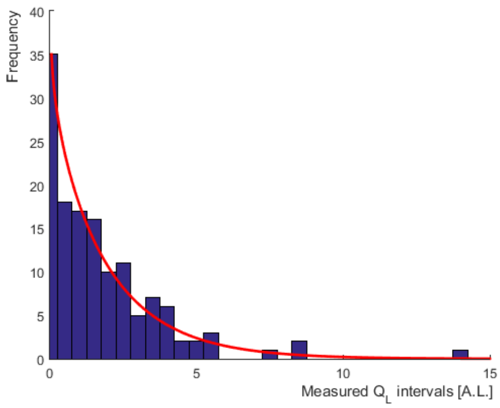

Figure 8. Distribution of the overall results and the parametrized Gamma distribution (red curve).

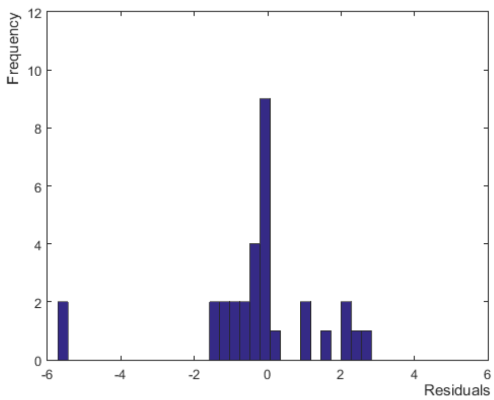

Figure 9. The residuals calculated by using the parametrized Gamma distribution. The chi-square per degree of freedom is 0.67.

study). We also must notice that the median is $\times 1.31$ A.L. and the probability to obtain $Q_{\mathrm{L}} < \times 1$ A.L. is 41.4%. Moreover, the 35 MM Quads corresponding to the higher bar in the distribution in the class $\times 0 - 5$ A.L. concern those that was well tight - in the vicinity of the sensitivity which is around $\times 0.1$ A.L. We also notice that the theoretical, feasible limit lies in the same class, $\times(0.11 \pm 0.03)$ A.L.

During the gas tightness test there is an impact of barometric pressure and temperature variations (both affect in anti-correlation). The barometric variations present a stochastic character and thus, elaborate in a long term period, it fluctuates around its mean value. The room temperature variations present a periodic - but not harmonic in shape - due to day and night variation. Consequently, this also fluctuates around its mean value in a long term period. Thus we can conclude that these parameters affected mainly the rms deviation and much less the mean of the obtained results.

The barometric pressure in time is completely unpredictable, as we can see in any record constituting a chaotic-like time series. Therefore, it is very hard to perform a correction to the gas leak rate measurement. Thus, we simply calculate the average between two successive maximum and minimum values (between peak and valley or vice versa), considering that this value corresponds to the turning point of the barometric pressure variation. Nevertheless, its gradients of variation present some maximum absolute values. Performing simultaneous gas leak rate measurements of the IP and HO sides of a LM type MM Sector, we have found that the impact of the barometric pressure was roughly $-1\times$ A.L. for a variation rate of +1 mbar/h (anti-correlation).

Let us now estimate the scale of the impact to our measurements. Scrutinizing the daily QFE data from Geneva's Cointrin Station from December 8 to 14 in 2020, we have found that the maximum constant rate of variation at many hours in a day is at the level of ± 0.70 mbar/h. Because a gas tightness test typically lasts 4 hours, the maximum effect of the barometric pressure is estimated at $\mp \times 0.70$ A.L. Therefore the average effect on each measurement is estimated at the levels of $\mp \times 0.35$ A.L. For the MM Wedges of SM type the effect should be $\mp \times 0.22$ A.L. due to a smaller volume by 1.6 times.

5. Percent oxygen monitoring

5.1. Detection technique and calibration

Because the oxygen is an electronegative gas, its contamination in the gas mixture Ar+7% CO_2 causes a drop-off to the "mesh transparency" as well as to the gas amplification of a MM detector. The impact of the presence of oxygen was studied by the well-known and widely used simulation tool-kit Garfield++. The monitoring of the percent oxygen can help us to estimate this suspected drop-off in the MM Quads and Wedges. The technique we used is based on low cost Oxygen Probe Analyzer (OPA) from AMI, model 60 equipped with sensor of type P3 which is tolerant to CO_2. It operates at continuous gas flow in the range from 3 L/h to 63 L/h. A custom made configuration at very low full scale (1% in our case) was requested from the manufacturer and it constitutes a great advantage providing very high precision of the order of 0.1%. At CERN we use three OPAs, the OPA-1, OPA-2 and OPA-3 in three different locations: at NSW (Bldg 191), at GIF++ (Bldg 887) and at BB5 Cosmic Ray Stand-CRS (Bldg 899).

5.2. Signal analysis and indirect calibration

In the NTUA Lab we tested the OPA-1 in transient transport of a finite volume of trapped atmospheric air, as seen in Fig. 10. The provided voltage output signal corresponds to Transient State Flow (TSF). By using appropriate shut-off valves this air volume pass through the OPA's sensor and shows a voltage output pulse (see Fig. 11) having a 3^{rd}-degree semi-gaussian shape in the best fit. By integrating this pulse we can determine the partial volume of oxygen and the air volume after conversion. The methodology we used was the following: the TSF signal expresses the instant contamination of oxygen when the argon plus the air (nitrogen and oxygen) passes through the OPA. Therefore, the partial volume of oxygen can be calculated by integrating the recorded curve of the percent oxygen contamination, let $x(t)$. The "carrier" gas (argon) is regulated to an arbitrary flow rate Q and thus the flow rate of oxygen should be, $Q_x = x(t)Q = \mathrm{d}V_x/\mathrm{d}t$. The flow rate of argon is regulated to be constant during the measurement and doesn't affect the TSF signal. Therefore, the partial volume of the oxygen should be

$$V_x = \int_0^{t_s} x(t)Q\mathrm{d}t = Q\int_0^{t_s} x(t)\mathrm{d}t = Q\,I \tag{2}$$

where, t_s is the sensor's time which is chosen to be significantly large (much greater than the time constant of the sensor). Nevertheless the curve is asymptotic and the integration can theoretically be evaluated up to infinity.

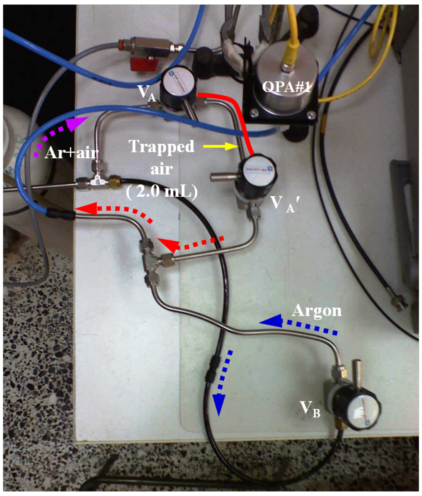

Figure 10. Photo of the setup for studying the OPA transient response. The trapped air (red) passes through the oxygen sensor of OPA.

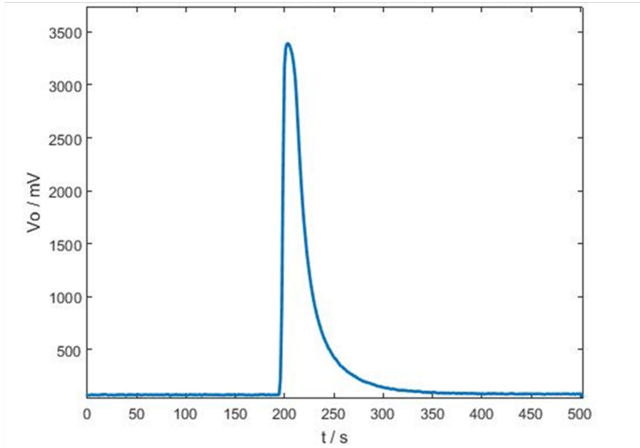

Figure 11. Pulse-shape response of the voltage output of the OPA obtained with 4.25 L/h flow rate. By integration we can determine the volume of the trapped air.

Figure 12. Photo of the “briefcase” setup (OPA-3) for monitoring the percent oxygen of a Double Wedge in Cosmic Ray Stand in BB5 at CERN.

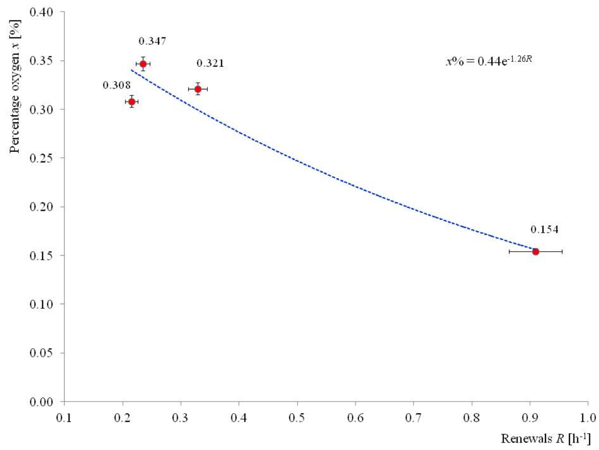

Figure 13. Plot with the obtained data of percent oxygen at three locations at CERN: from left to right, at GIF++ (1st data point), at NSW (2nd data point), at BB5(3rd data point) and at GIF++ (4th data point). The red curve is a fitting by using exponential function given in the plot area.

5.3. Preliminary results

For the percent oxygen monitoring of the MM wedges at CERN we connect the OPAs at the output line of the detectors where the gas mixture flows constantly. In this mode of operation the OPA’s sensor and provides a voltage output, we call Steady State Flow (SSF) signal, from which we can determined the percent oxygen. In Fig. 12 the complete setup with OPA-3 installed in BB5 Lab at CERN is shown, while in Fig. 13 a plot of the obtained measurements in three different locations, as a function the renewal rate, is illustrated. The obtained percent oxygen has been normalized to the renewal rate, $R = Q/V$, of the detector system under study, where Q is the flow rate and V the volume of the system (e.g. a Quad alone, Single or Double Wedge or even a combination of them). These values of percent oxygen, converted to percent air dividing by 0.2046, allows us to determine the drop-off in mesh transparency of the MM detector based on simulations. If we implement this procedure we conclude that the mesh transparency drop-off is roughly in the range from 0.76 to 0.86. The conversion formula from voltage to percent oxygen is, $x\% = (V_o - V_{ofs})/(V_{fs} - V_{ofs})\ \%$, where V_o is the voltage output of the sensor, V_{ofs} is the offset value with no oxygen contamination and V_{fs} is the full scale voltage output of the sensor corresponding to 1% oxygen contamination. Especially, for determining V_{fs} we had applied a premixed gas mixture of Ar+1% oxygen from a commercial bottle with accuracy of 1%.

6. Conclusions

Several projects regarding the gas system of the Micromegas New Small Wheels we have developed during last 6 years. In particular, for the gas tightness of the Micromegas Quads and Wedges, we have introduced a novel method, the FRL, which is reliable and precise, even in the case of variable gas volume. Its performance has been verified at CERN and thereafter we have implemented it in the end-to-end validation tests. The associated baseline devices and the portable stand-alone ones were stable during the integration and commissioning period. The obtained overall-final statistical distribution of the leak rate of Micromegas Quads shows a Gamma distribution shape according to our parametrization. The relatively large rms deviation is due to the impact of the barometric pressure and Lab temperature variations. In addition, we have developed and introduced a precise and low cost percent oxygen monitoring technique, based on Oxygen Probe Analyzers, by which we are able to conclude regarding the drop-off of the performance of the Micromegas Wedges. We would also like to emphasize that the above methods and devices could used also in many similar applications.

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