Gas System Design and Functional Performances of the NSW Micromegas Quadruplets for the Muon ATLAS Upgrade

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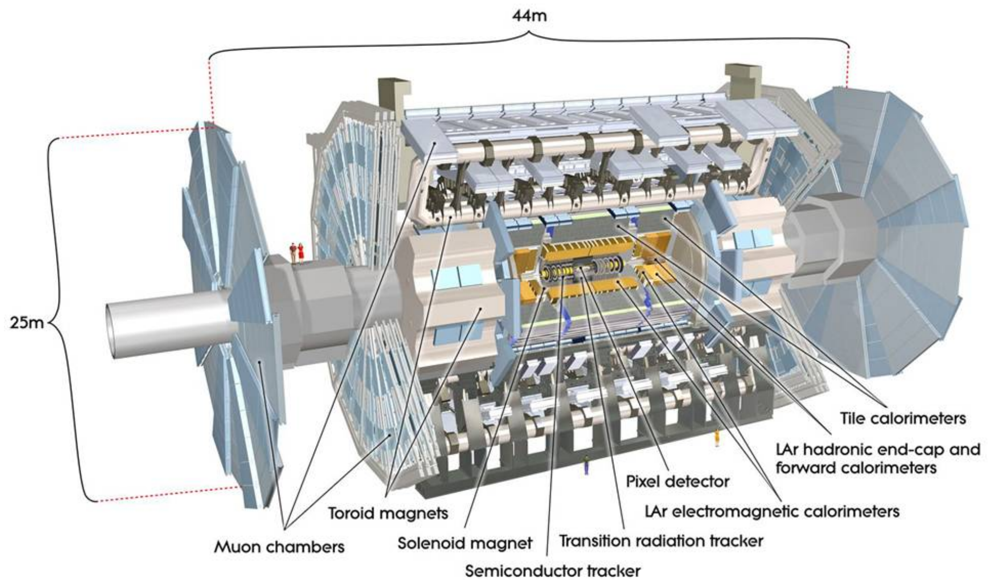
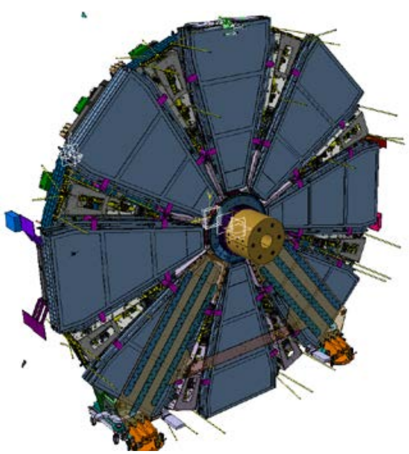
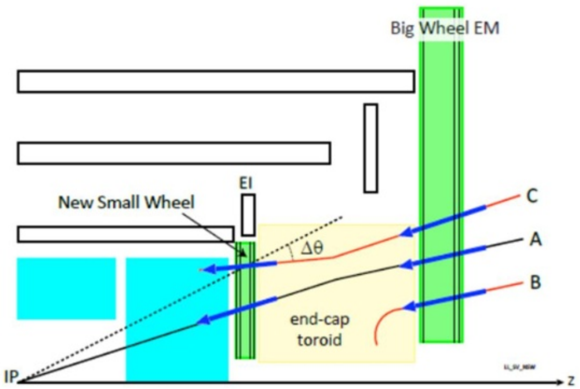
Outline

- *ATLAS Upgrade NSW: Overview of the gas system design*
- *Proposed design solutions and development/production of the specific gas components (2014-integration: 2018)*
- *Determination/Prediction of the "Theoretically Feasible Sealing" (TFS) of the Micromegas Quadruplets (end of 2016-2017)*
- *Theoretical approach to the transparency drop-off of a Micromergas Moodule due to air diffusion mechanism (2017-in progress: 2018)*
- *The proposed-novel Gas Tightness Test method (FRL), its implementation and integration in BB5 at CERN (proposed: 2015-operational quad: 2018)*
- *Conclusions*

ATLAS UPGRADE: New Small Wheel



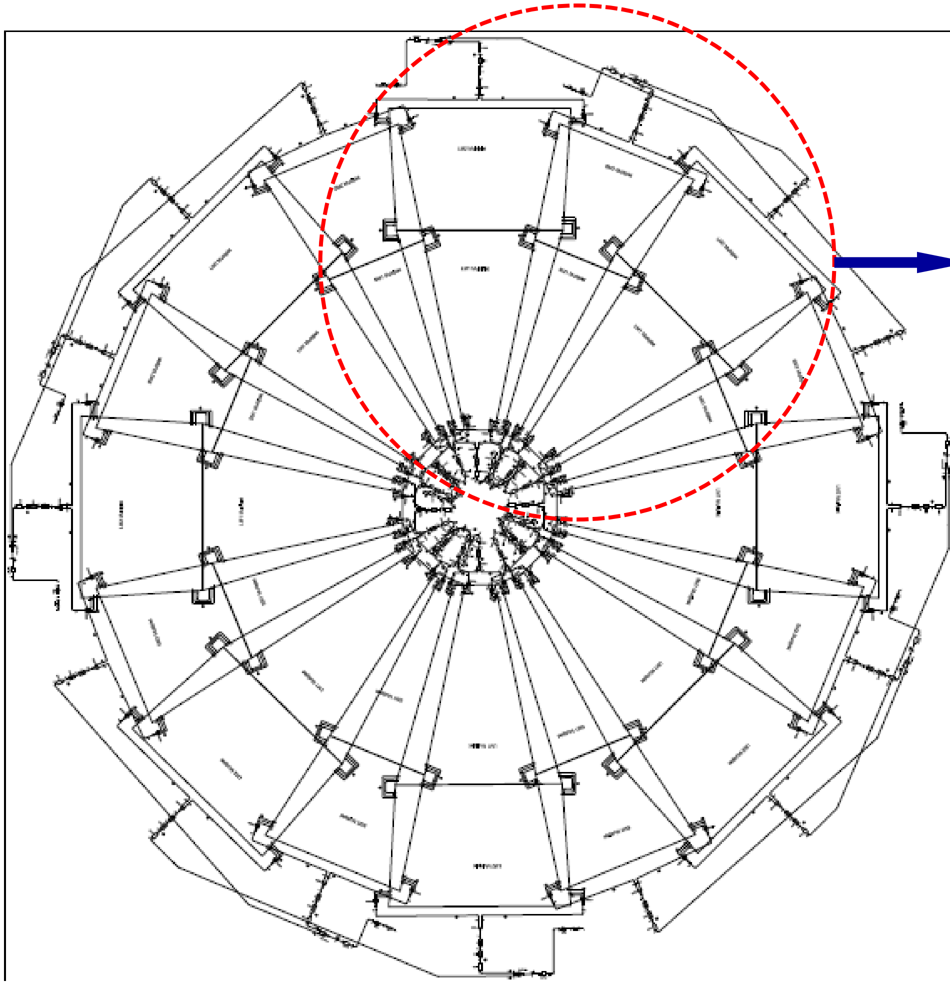




$$1.0 \leq |\eta| \leq 2.7$$

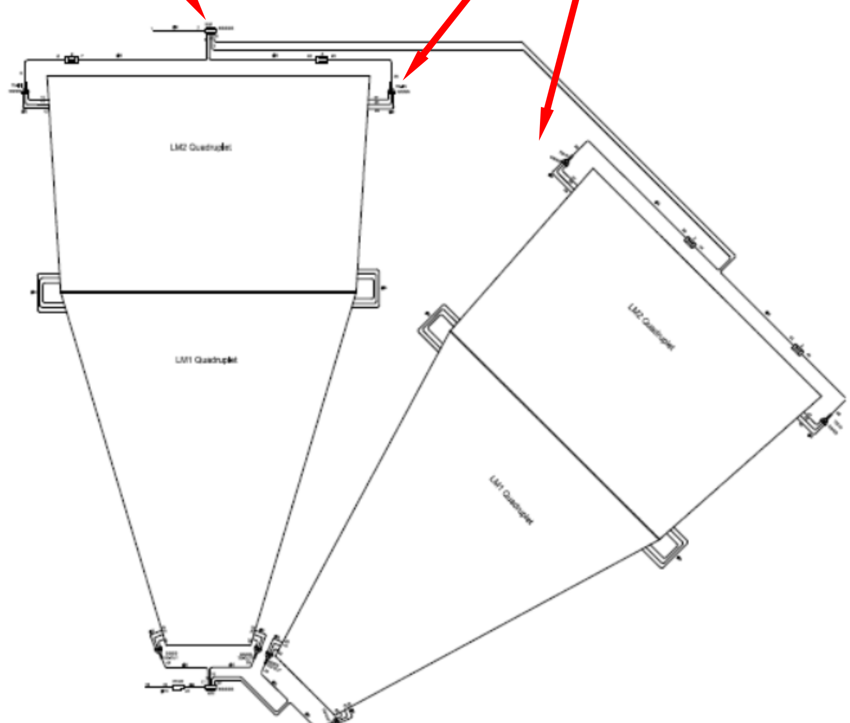
Gas system of the NSW Micromegas

- 16 gas channels should provide gas mixture (Ar+7% CO_2 at around 3 mbar) to each NSW
- Each channel provide gas either to two LM wedges or to two SM wedges
- The gas inlet comes from the outer rim and the gas outlet goes to the inner rim.

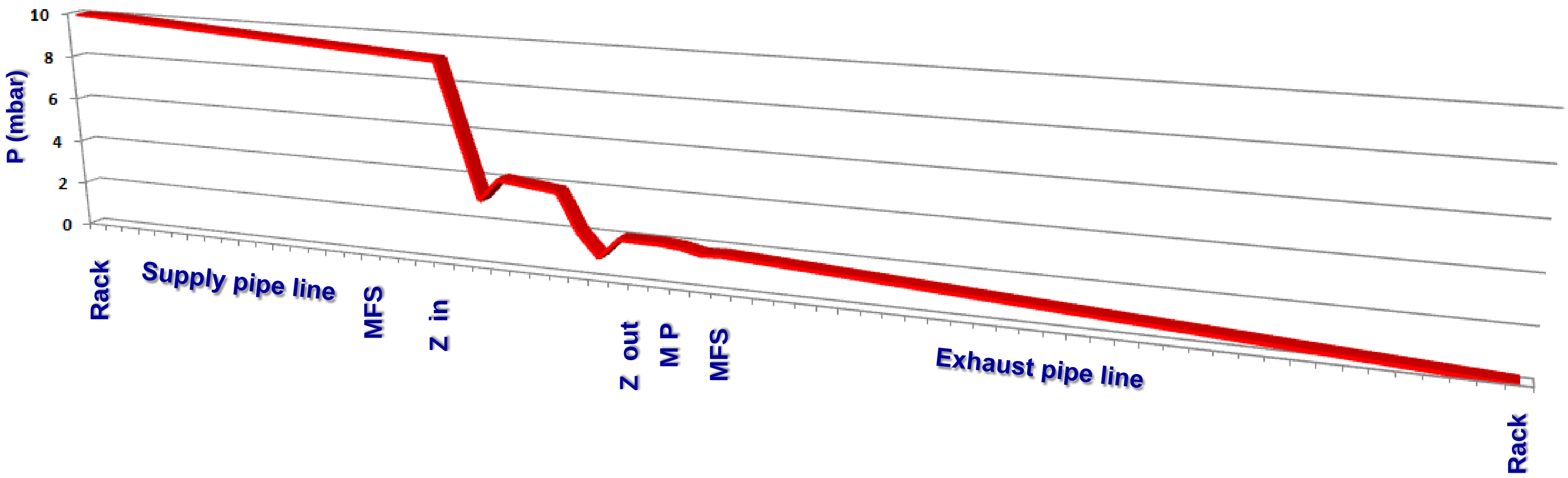


“Trident” manifolds

“Wedge” manifold

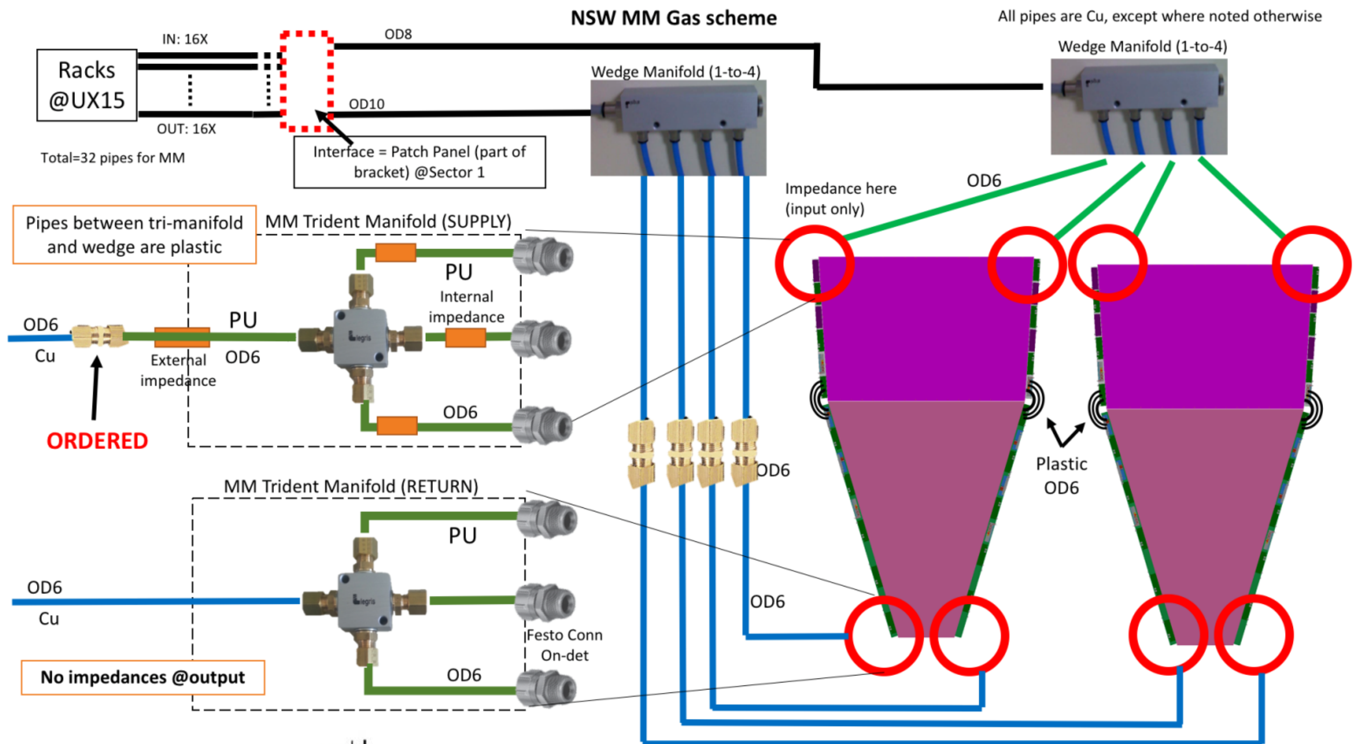


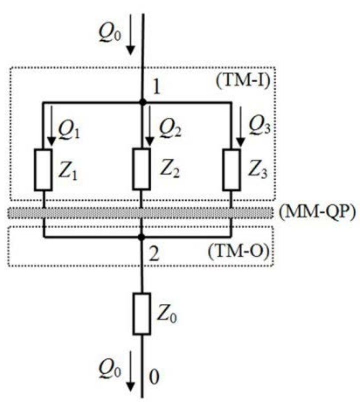
Pressure drop along a gas channel

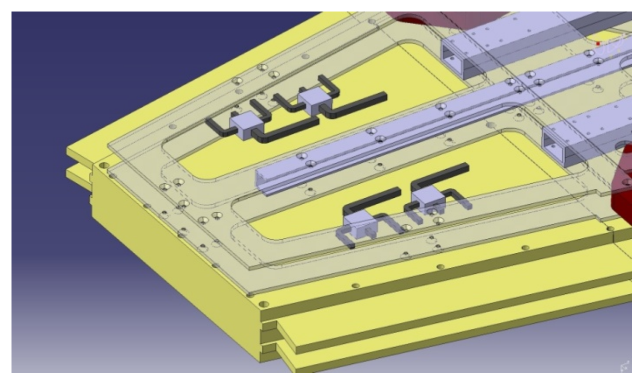


Horizontal axis not in scale

Specific gas components (impedances & manifolds)







Results and evaluation method (in trial samples)

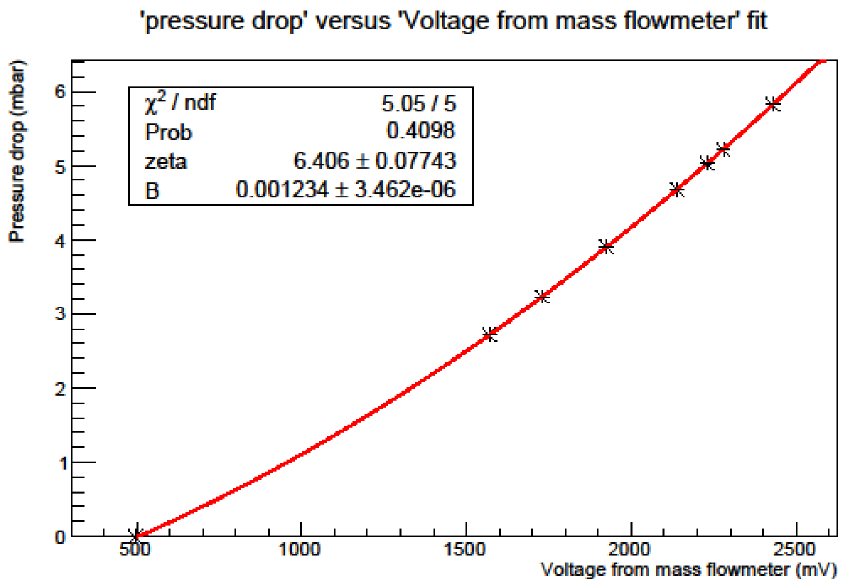
Zi	IMPEDANCE ID	ΔP (mbar) - FORWARD	ΔP (mbar) - BACKWARD	MEAN ΔP (mbar)	ΔD/D (%)	ESTIMATED D (μm)
Z1	ZLM-370-11800-01	3.79	3.87	3.47	-0.2	369
Z2	ZLM-370-11800-02	3.67	3.79	**RMS ΔP (mbar)**	0.6	372
Z3	ZLM-370-11800-03	2.93	2.71	0.46	8.0	400
Z4	ZLM-370-11800-04	3.51	3.52	**REL. RMS (%)**	2.4	379
Z5	ZLM-370-11800-05	3.14	3.24	13.1	5.0	389
Z6	ZLM-370-11800-06	2.95	2.92	**MEAN ASYM. (%)**	7.1	396
Z7	ZLM-370-11800-07	4.22	4.42	-0.5	-4.2	354
Z8	ZLM-370-11800-08	4.14	4.36	**RMS ΔD (μm)**	-3.6	357

Theoretical model used for the design

$$\left(\Delta p\right)_{S_1 S_2} = b\left\{\frac{8\rho}{\pi^2 D^4}\left[a k_{LC} + k_{LE}\right]Q^2 + \frac{128 L\eta}{\pi D^4}Q\right\}$$

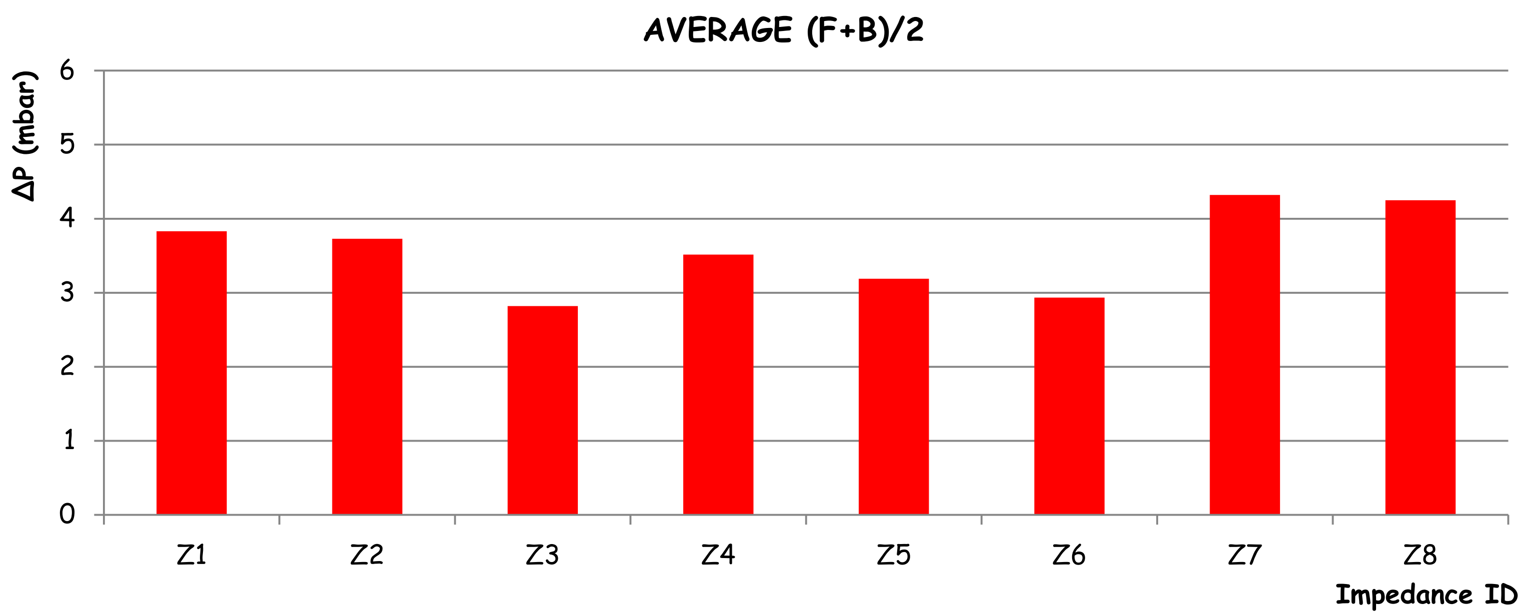
$a = 1$ (geom. factor), $b = 0.94$ (calibr. factor)

By fitting using the voltage output of the Mass Flow Sensors we can determine the diameter of the channel as a free parameter



Variations in the diameter of 2 μm can be detected by using the gas flow model

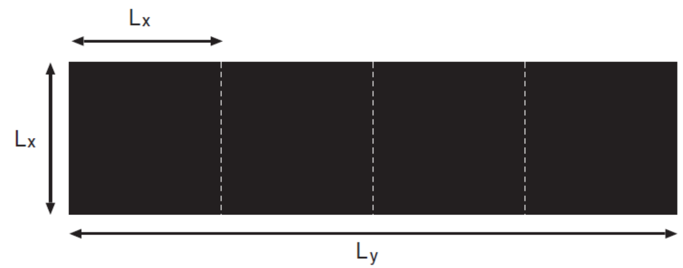
“Gas Impedances”: production in Greece



<u>CNC Machinery</u>: A. & G. Boukis
<u>Method</u>: Die-Sinking EDM (Electrical Discharge Machining)
<u>Ordered pieces</u>: 571 (included 8 samples)
<u>Channel diameters</u>: 0.370, 0.420, 0.900, 1.000 mm
<u>Required uncertainty in the diameter</u>: < ±15 μm (achieved <5 μm)

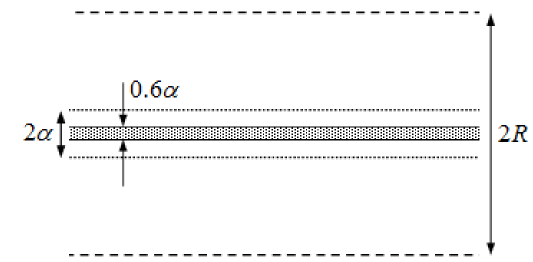
Leak rate determination of the Micromegas Modules

According to the Poiseuille Law for a Newtonian fluid and for a rectangular cross section percolation channel of height u_c and width and length λ_c ($u_c << \lambda_c$).



$$Q_L = a\frac{L_y}{L_x}\frac{u_c^3}{12\eta}\Delta P$$ **where,**

$$L_x = \frac{0.3\times 4P_0R}{E^*} = \frac{1.2P_0R}{E^*} = \frac{1.2P_0R\left(1-\nu^2\right)}{E}$$ **and** $a \approx 1$



We have to cope with 1-variable and 8-parameters !

$$Q_L(P_0) = \left(\frac{\pi L_y}{14.4R}\right)\left(\frac{E^*}{P_0}\right)\left(\frac{\Delta P}{\eta}\right)u_c^3 = \left(\frac{\pi L_y}{14.4R}\right)\left(\frac{1}{f(\varepsilon)}\right)\left(\frac{\Delta P}{\eta}\right)u_c^3(h_{0,A}^2, H, q_0, f^{-2}(\varepsilon))$$

$$f(\varepsilon) \equiv \frac{P_0}{E^*} = \frac{1}{3}\left[\left(1-\varepsilon\right)-\left(1-\varepsilon\right)^{-2}\right]$$

Pressure difference

Surfaces roughness amplitude

Rubber contact length

Roll-off wave number

Squeezing pressure

Rubber's radius

Hurst exponent

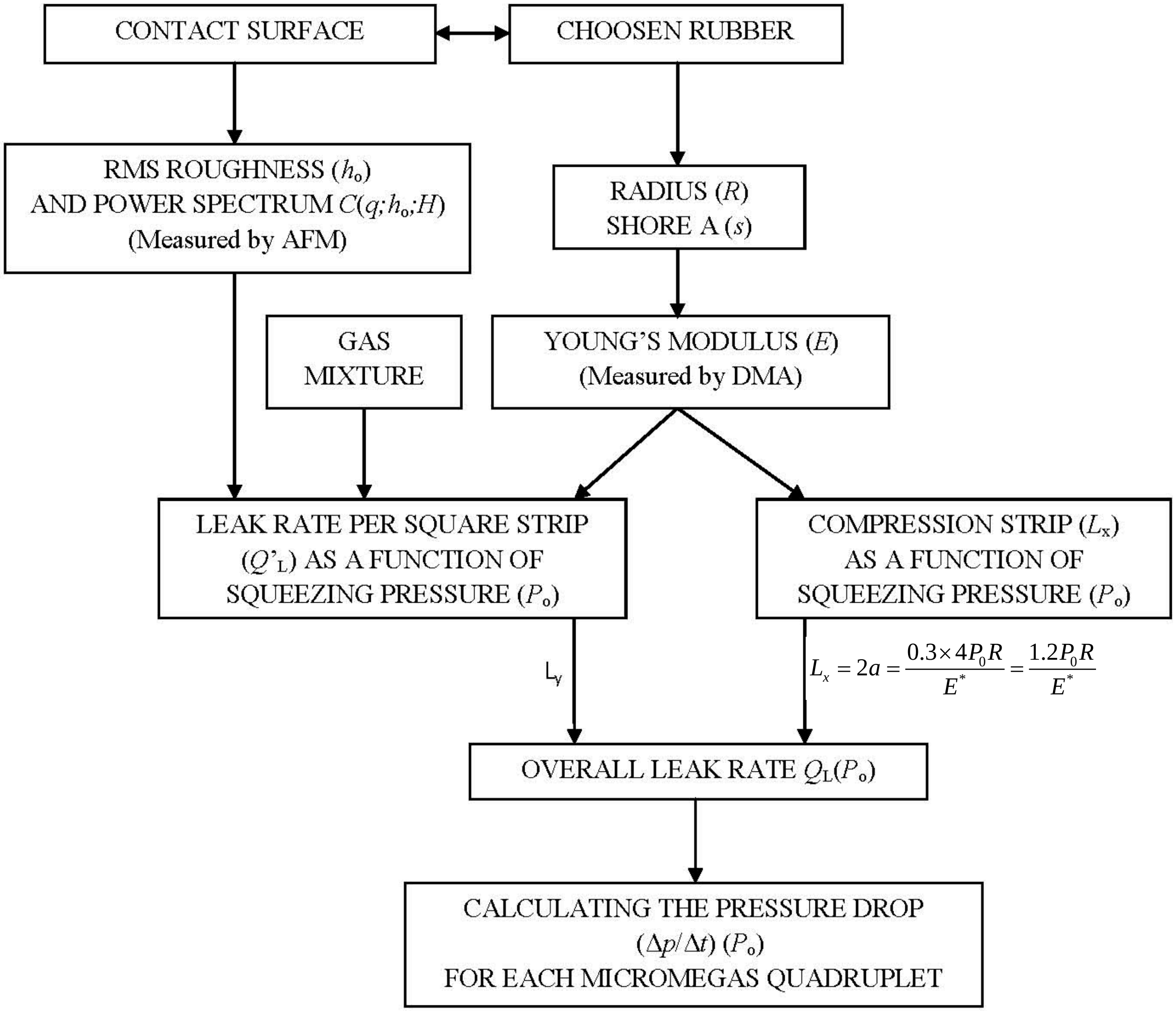
Squeezing ratio

Gas viscosity

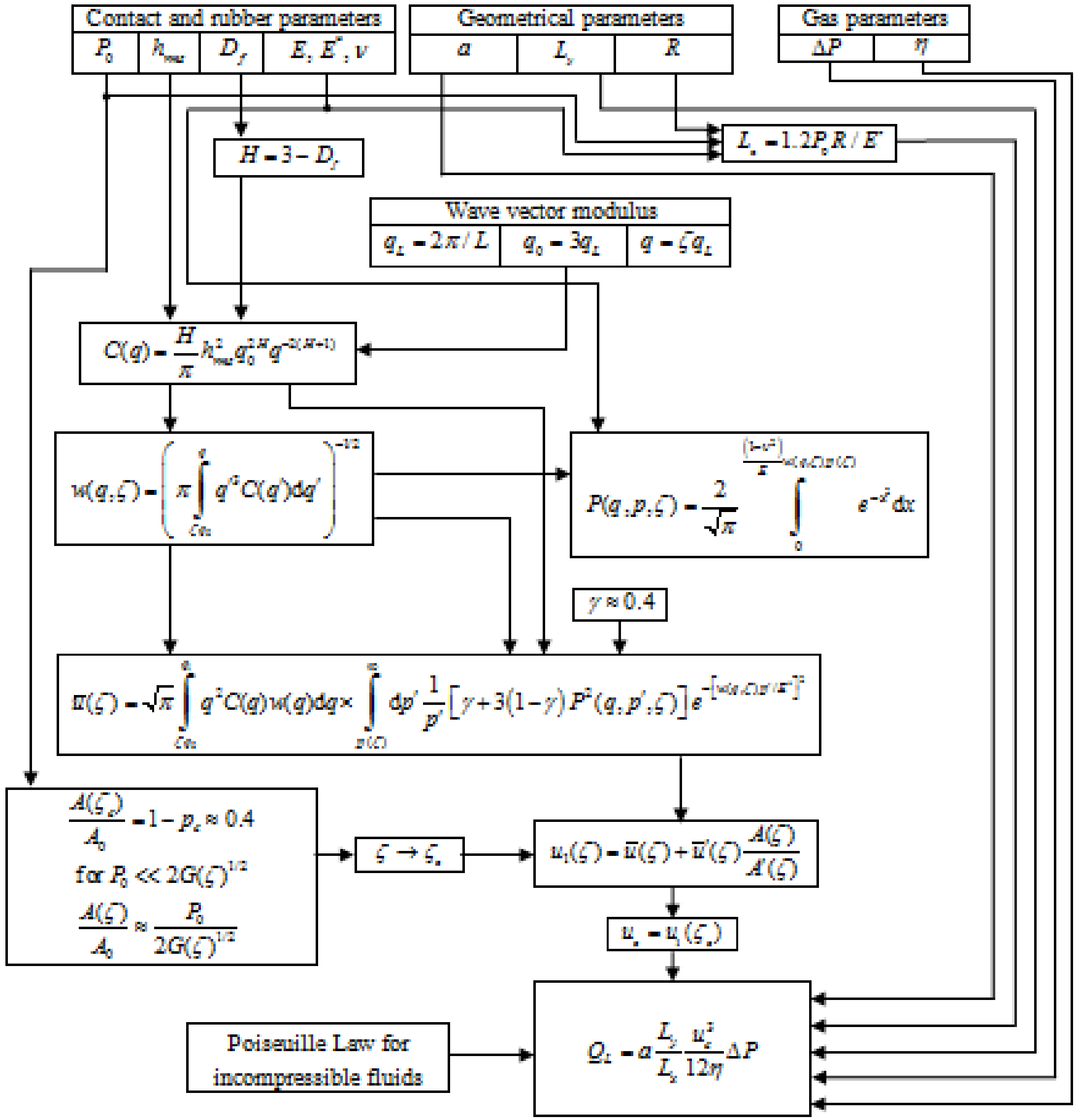
Apparent contact separation at critical magnification

Plane elastic modulus

Building blocks of the procedure



Calculation methodology



Solution for self-affine fractal surfaces

<u>First step</u>: after some analytical work, we found the formula for the critical magnification:

$$\zeta \equiv \zeta_c = \left(1 + \frac{1}{\dfrac{\pi^2 C_0 q_0^{2(1-H)}}{50 P_0^2 (1-H)} \left(\dfrac{E}{1-\nu^2} \right)^2} \right)^{\frac{1}{2(1-H)}}$$

<u>Second step</u>: calculating the surface separation. In this analysis we use the approximation that the surface separation at critical magnification $u_1(\zeta_c)$ can be used in place of the rms roughness at this magnification.

$$h_{0,r}(P_0)\Big|_{\zeta=\zeta_c} \approx \frac{h_{0,A}}{\sqrt{2}} \left(1 + \frac{1}{\dfrac{\pi^2 \dfrac{H}{2\pi} h_{0,A}^2 q_0^2}{50 P_0^2 (1-H)} \left(\dfrac{E}{1-\nu^2} \right)^2} \right)^{\frac{H}{2(H-1)}} = \frac{h_{0,A}}{\sqrt{2}} \left(1 + \frac{1}{\dfrac{\pi H h_{0,A}^2 q_0^2}{100(1-H)} \left(\dfrac{E^*}{P_0} \right)^2} \right)^{\frac{H}{2(H-1)}} \approx u_c(\zeta_c)$$

Obtained "Theoretically Feasible Sealing" for the LM2 MM QP: $Q_{L,TFS} = 4 \pm 1$ mL/h

Electron's attachment by air (due to oxygen)

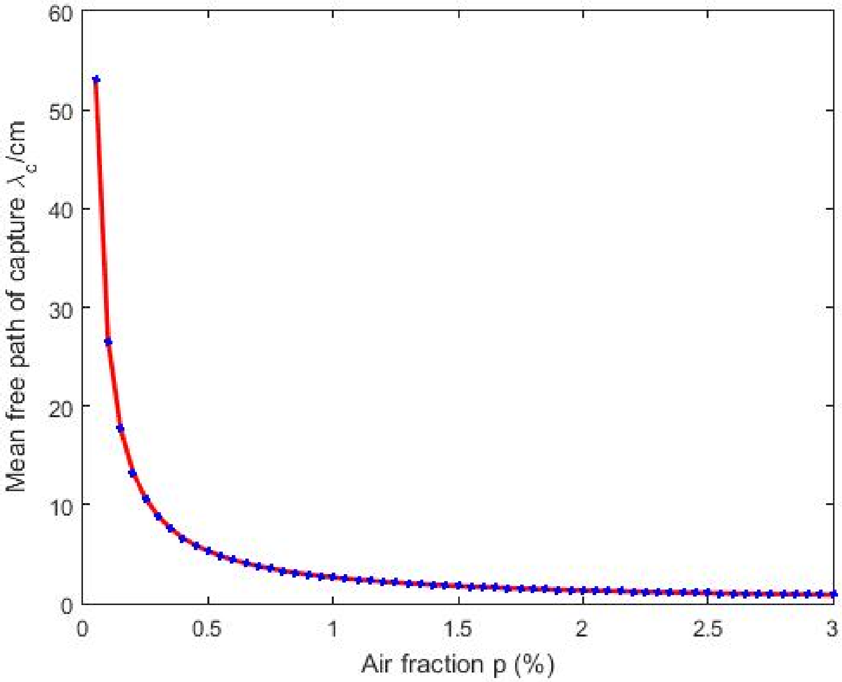
$$n = n_0 e^{-x/\lambda_c} \qquad \lambda_C = \sqrt{\frac{m}{2\varepsilon_k}} \frac{w}{N \cdot h \cdot p \cdot \sigma(\varepsilon_k)} \qquad \varepsilon_k = \frac{eED(E)}{w(E)}$$

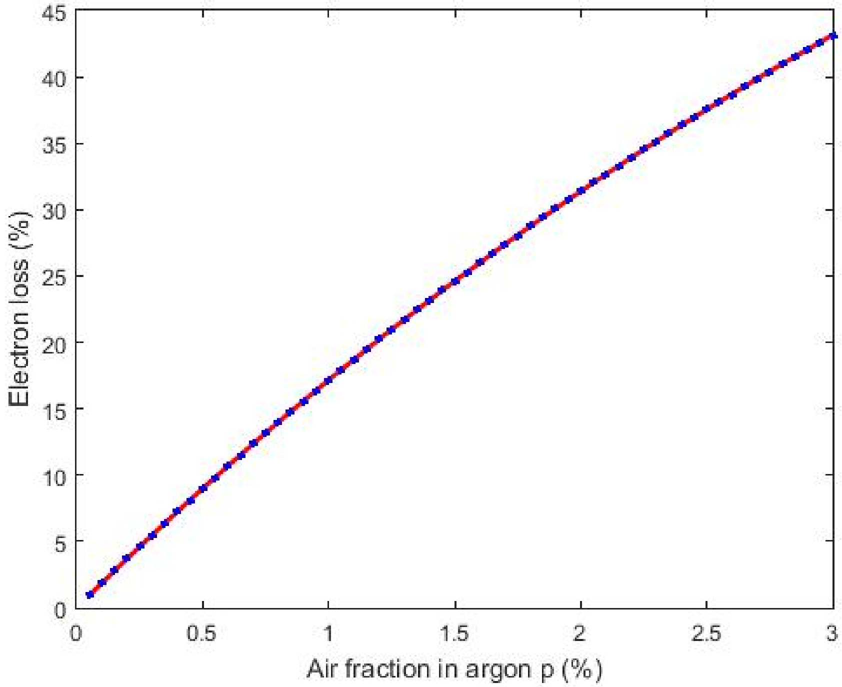
λ_c : the mean free path for capture of electrons

***m*: the mass of the e$^-$**
ε_k: the characteristic kinetic energy of the e$^-$ (related to the energy distribution of the e$^-$) defined by
***E:* the electric field**
***D*: the diffusion coefficient**
***w:* the drift velocity of e$^-$**
***N*: the molecules concentration of the detector's gas**
***h*: the probability of electron attachment in air**
***p*: the mole percentage (fraction) of air in the gas**
$\sigma(\varepsilon_k)$: the Ramsauer cross section for electrons in a gas

Transparency in the drift region: $T = \dfrac{n}{n_0} = e^{-x/\lambda_c}$

Air fraction in pure Ar for Micromegas parameters





Simulations with “Garfield” with Argon+7%CO_2 give very similar result (see Dipl. Thesis of Ch. Kitsaki)

1D continuous diffusion (gas at rest)

Fick's 2st law for 1-dimensional diffusion (1st law+continuity equation)

$$\frac{\partial C(x,t)}{\partial t} = D\frac{\partial^2 C(x,t)}{\partial x^2}$$

I - 1) Initial condition $C(x,0) = C_0$

B-2) Boundary condition (being constant) $C(0,t) = C_a$

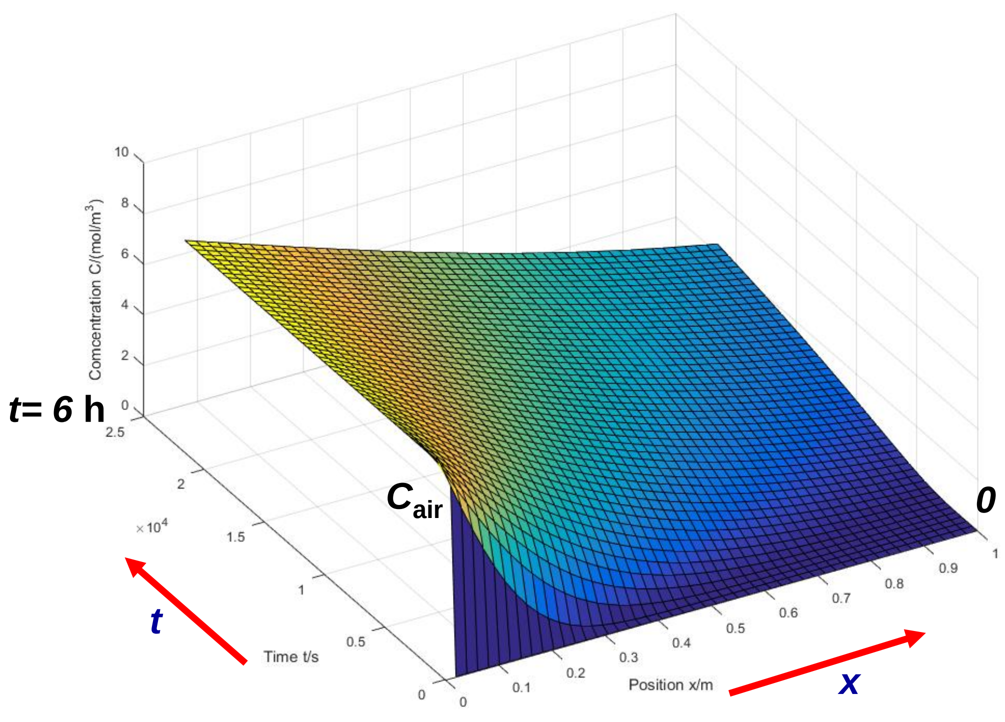
B-3) Boundary condition (being constant) $C(\infty,t) = C_0$

Solution for $0 \le x \le L: \quad C(x,t) = C_a + \left(C_0 - C_a\right)\mathrm{erf}\,\frac{x}{2\sqrt{Dt}}$

Solution for $C_0 = 0: \; C(x,t) = C_a\left(1 - \mathrm{erf}\,\frac{x}{2\sqrt{Dt}}\right)$

Diffusion's space-time representation (R=0)

Graphical space-time representation of the solution using C_0=0 and C_a (atmospheric air mole concentration). The total time shown is equal to their nominal "renewal time" 1/R (6 hours) of the Micromegas Quadruplets.



1D dispersion with removal term (R>0)

The general partial differential equation containing a removal rate term is the following (semi-infinite medium with constant surface concentration):

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2} - RC$$

Where *C*(*x*,*t*) denotes the mole concentration of the air free to diffuse at a distance *x* at time *t* while *R* is the removal rate of the air (due to gas flow in our case) which is constant. The solution is

$$C(x.t) = \frac{C_a}{2}\exp\left(-\sqrt{\frac{R}{D}}x\right)\mathrm{erfc}\left(\frac{x-2\sqrt{RD}\cdot t}{2\sqrt{Dt}}\right) + \frac{C_a}{2}\exp\left(\sqrt{\frac{R}{D}}x\right)\mathrm{erfc}\left(\frac{x+2\sqrt{RD}\cdot t}{2\sqrt{Dt}}\right)$$

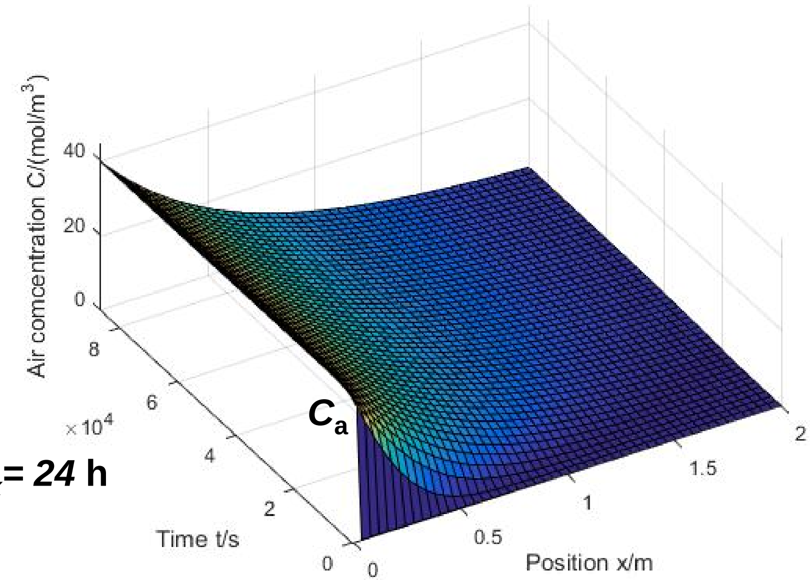
For the steady state solution $t \rightarrow \infty$ and *x*>> and finite we obtain

$$\lim_{t\to\infty} C(x,t) \equiv C(x) = C_a \exp\left(-\sqrt{\frac{R}{D}}x\right)$$

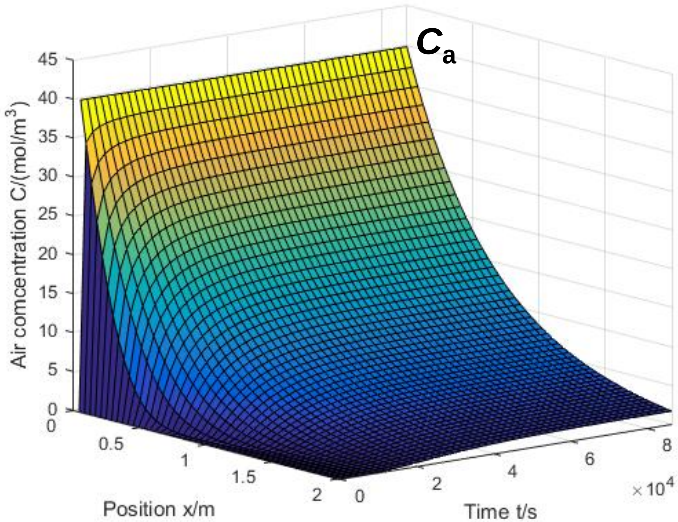
The steady state solution can be defined for d*C*/d*t* = 0

Space-time representation

Graphical space-time representation of the solution considering a permanent atmospheric air mole concentration C_a. The total time shown is equal to 4 "renewal times".



t_{max}= 24 h



t_{max}= 24 h

$$n_{air} = C_a \sqrt{\frac{D}{R}} \left(1 - e^{-x_{max}\sqrt{R/D}}\right)$$

Air mole fraction determination

$$n_{air} = \int_0^\infty C(x)dx = C_a \int_0^\infty \exp\left(-\sqrt{\frac{R}{D}}x\right)dx = C_a\sqrt{\frac{D}{R}}$$

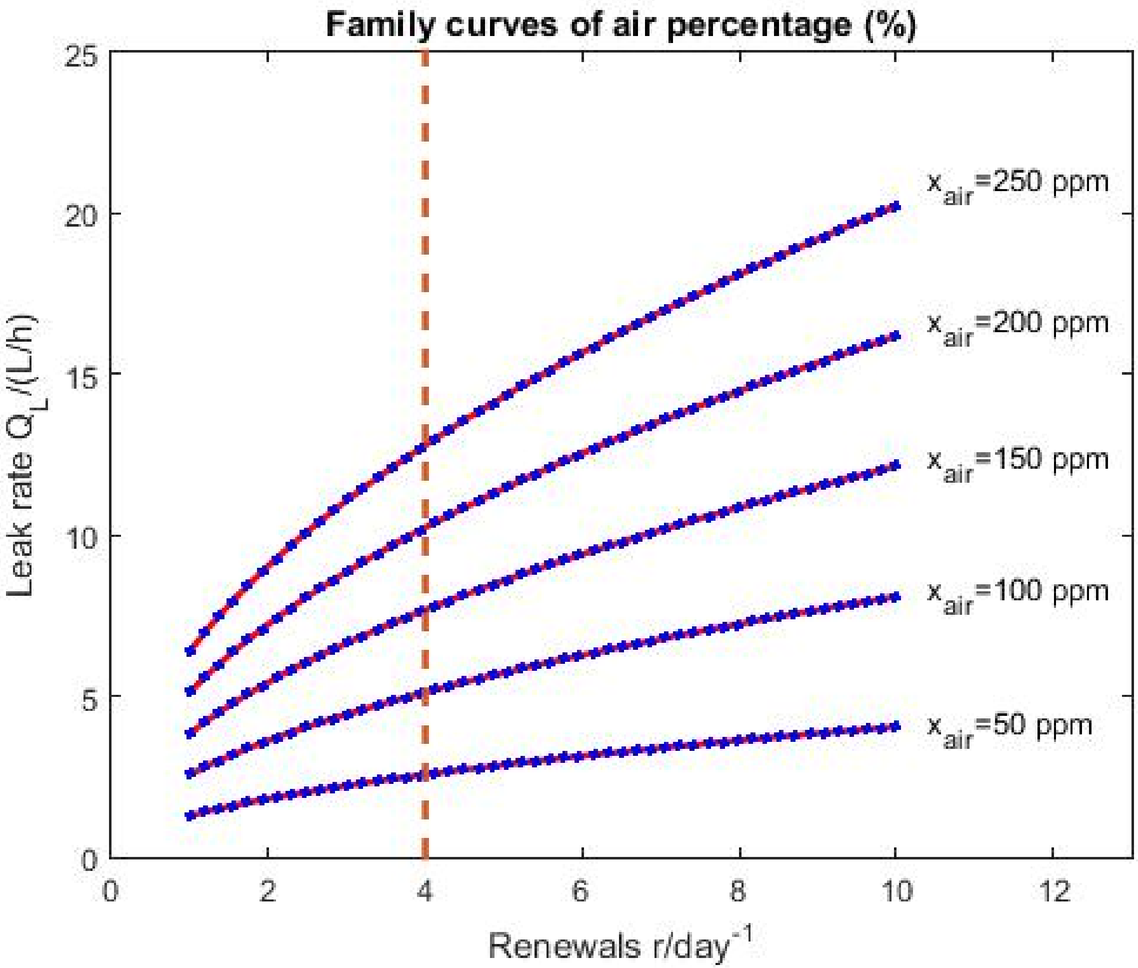
Integrating over the area A of the leakage hole and the half solid angle, 2π, from *r*=0 to a radius r_{max} we have

$$n_{air,3D} = \frac{2\pi C_a Q_L}{\upsilon}\sqrt{\frac{D}{R}}$$

$$x_{air} = \frac{n_{air,3D}}{\left[V(x_{\max})/V_{mol}\right]} = \left(1-e^{-r_{\max}\sqrt{R/D}}\right)\frac{2\pi V_{mol} C_a \sqrt{D}}{0.5\times\pi r_{\max}^2 h\upsilon}\frac{Q_L}{\sqrt{R}}$$

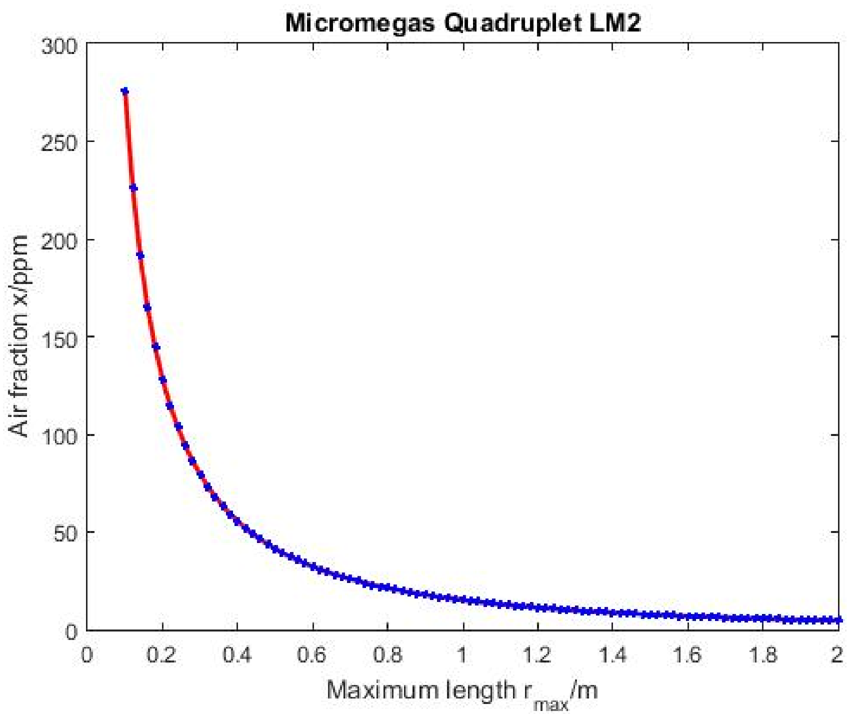
This is an approximation neglecting the detector's walls reflection, which corresponds to a more safe side. Simulations using COMSOL are also in progress)

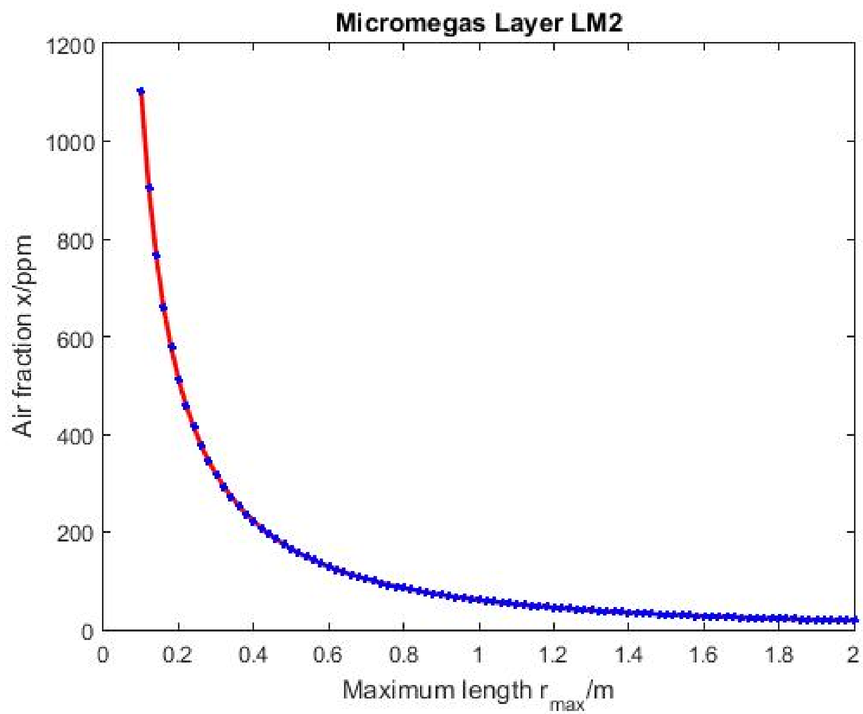
Family curves $f(Q_L,R,x_i)=0$ for the LM2 MM QP



These scales of mole fraction of air is very hard to be measured experimentally

Air mole fraction closer to the "leakage source"



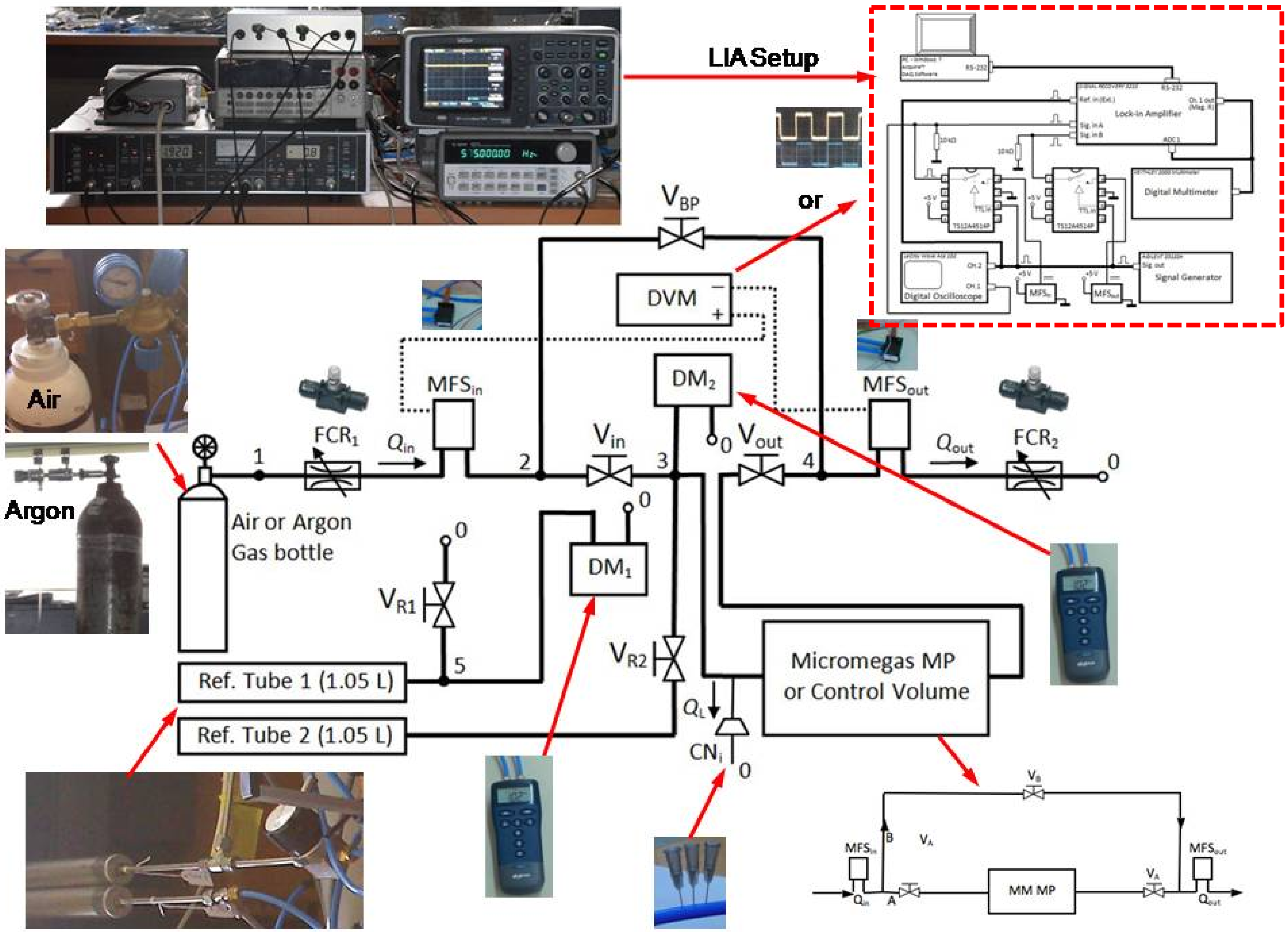


The air fraction x_{air} as a function of the radial distance from the leakage source in the chamber for a LM2 Quadruplet and for a LM2 Layer alone.

$$\frac{\Delta T}{T_0} = 1 - e^{-3.7\times10^{-4} Q_L} \qquad \frac{\Delta T}{T_0} = 1 - e^{-4\times3.7\times10^{-4} Q_L} = 1 - e^{-1.48\times10^{-3} Q_L}$$

- **The above results concern an overall (effective) *T* drop-off in the volume**
- **A renewal rate *R*=4 per day was considered.**
- **For leak rate equal to 2 L/h we obtain ΔT/T_o≈0.07 % and 0.3 % respectively**

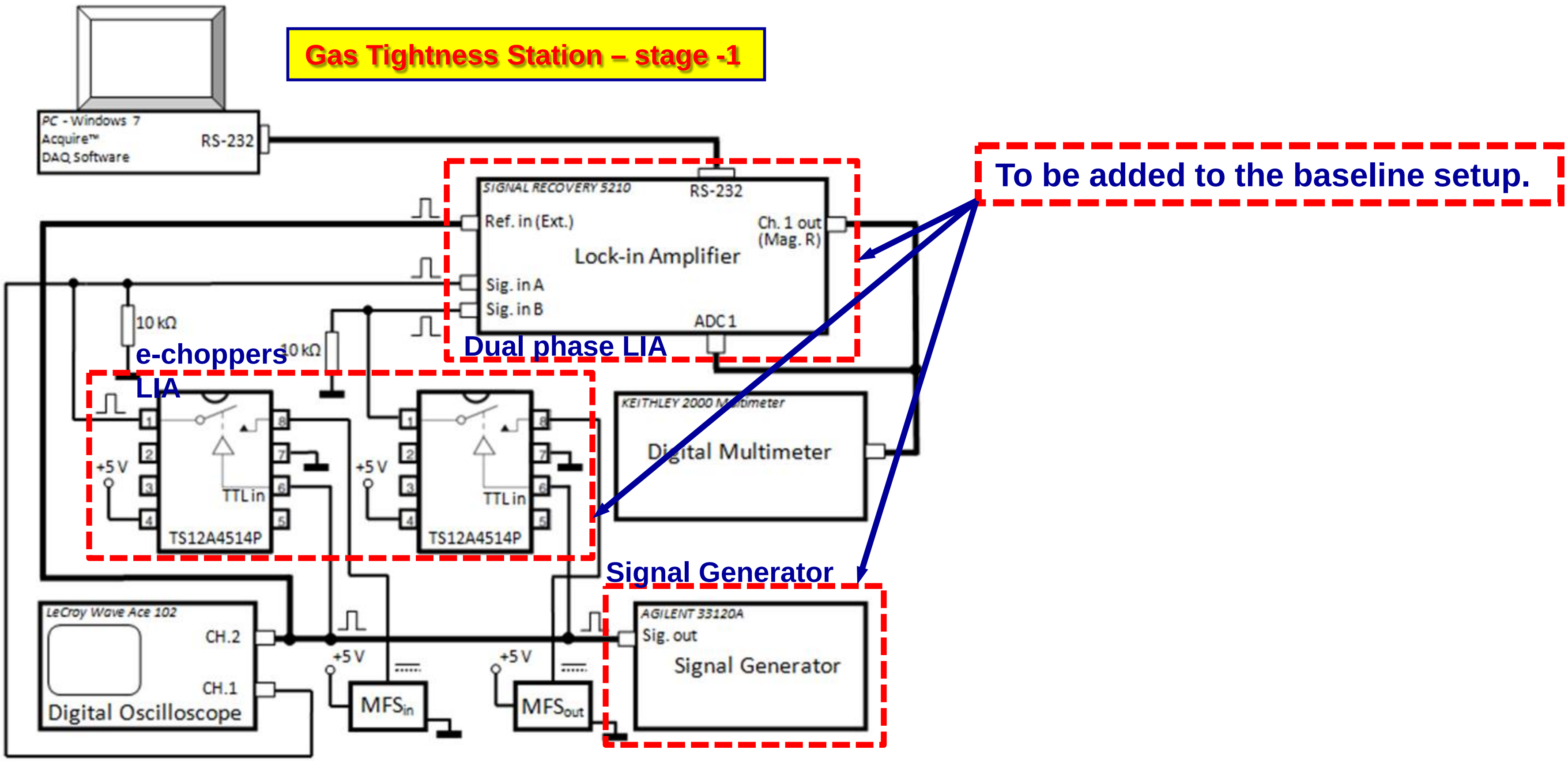
The introduced-novel gas tightness method: FRL



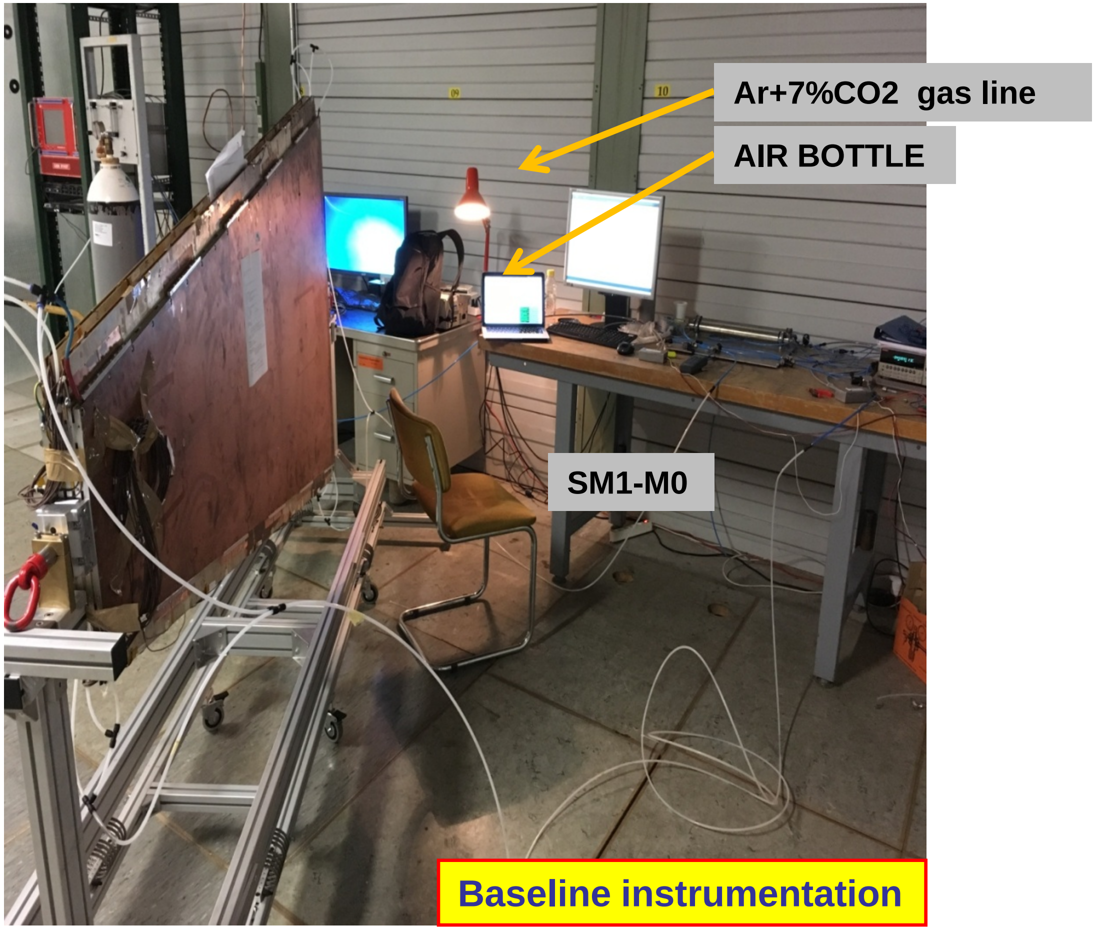
FRL: Flow Rate Loss, based on the mass conservation principle of the gas

Upgraded FRL setup

The achieved improvement on S/N ratio depends on the signal level. Typically, we achieve a S/N about 30 at the lowest expected levels of leakages. The analog dual phase LIA 5210 we used is a classical analogue model available in NTUA.

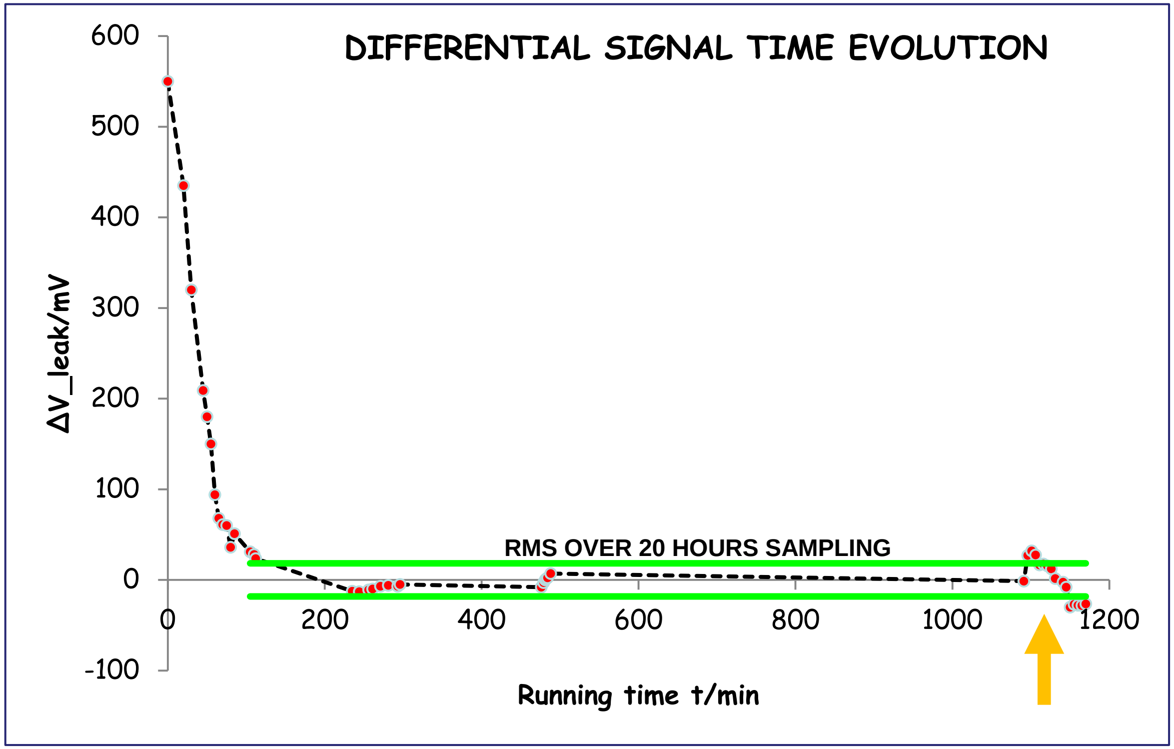


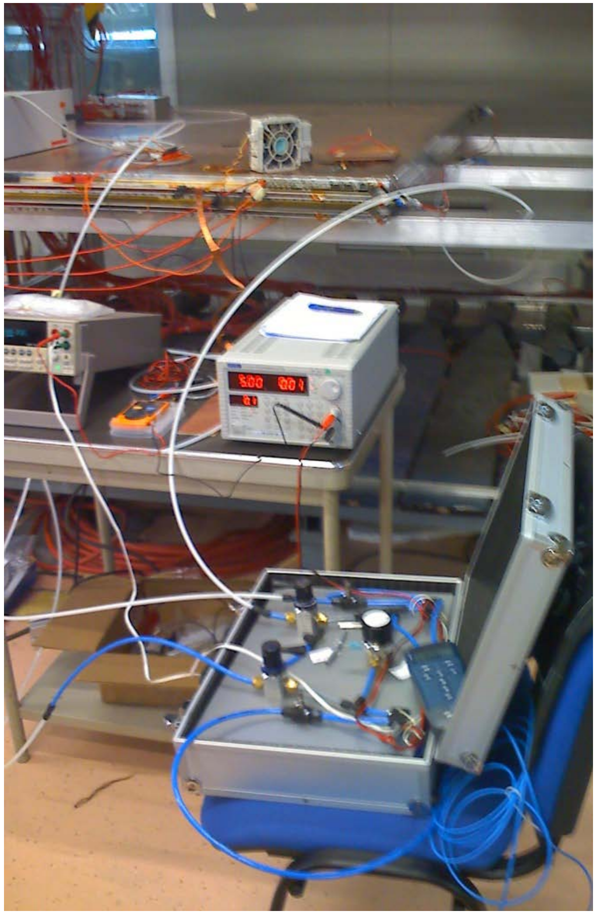
First test of the Gas Tightness Station (GTS) at BB5



- Two Mass Flow Sensors
- Digital differential manometer
- Field Point NI (16-bit ADC) with 4 channels in use
- WinCC-OA monitoring and control

Gas Leak Test of LM2-M0 at CERN





RESULTS NORMALIZED AT p=3 mbar		
(A) AVERAGE - overall ΔV (mV)	(B) AVERAGE - selected ΔV (mV)	NEEDLE 31G ΔV (mV)
0.25	**17.84**	**37.3**
RMS - overall	RMS - selected	TARE or OFFSET (mV)
18.20	**5.8**	**9.9**
LEAK RATE UPPER BOUND (mL/h)	LEAK RATE (mL/h)	LEAK RATE (mL/h)
12.2	**11.8**	**42±2 (overall)**
REFERRED TO THE NSW TYPICAL ACCEPPTANCE LIMIT OF LM2(=37 mL/h)		
0.33	**0.32**	**1.14**

A) $Q_L < 12 \pm 0.6(\text{syst.})$ mL/h

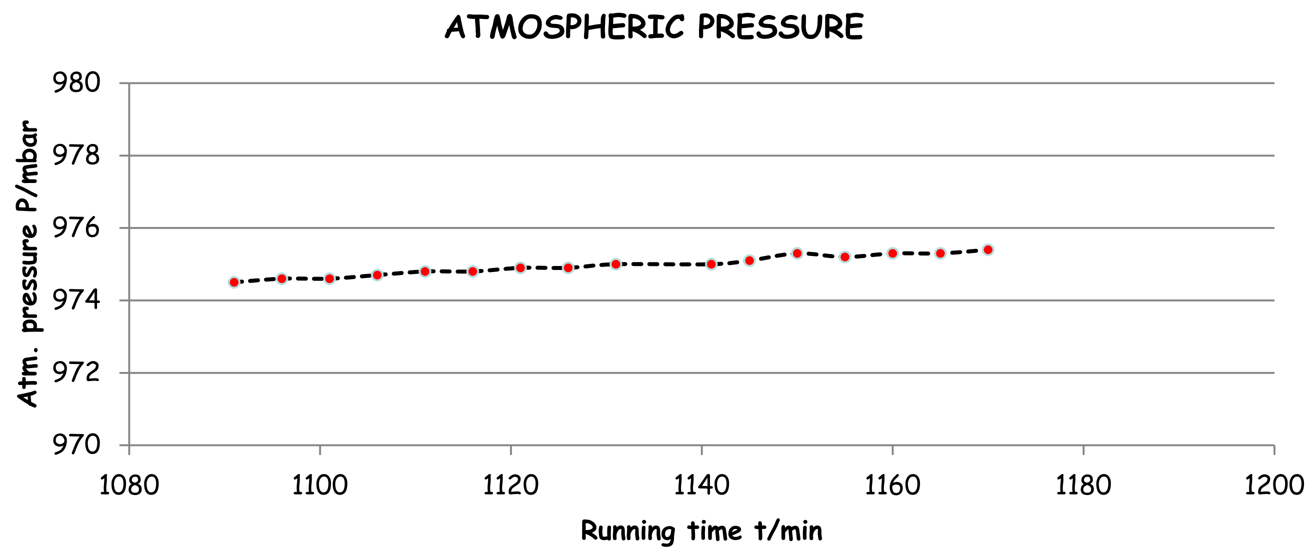
B) $Q_L = 12 \pm 6(\text{stat.}) \pm 0.6(\text{syst.})$ mL/h

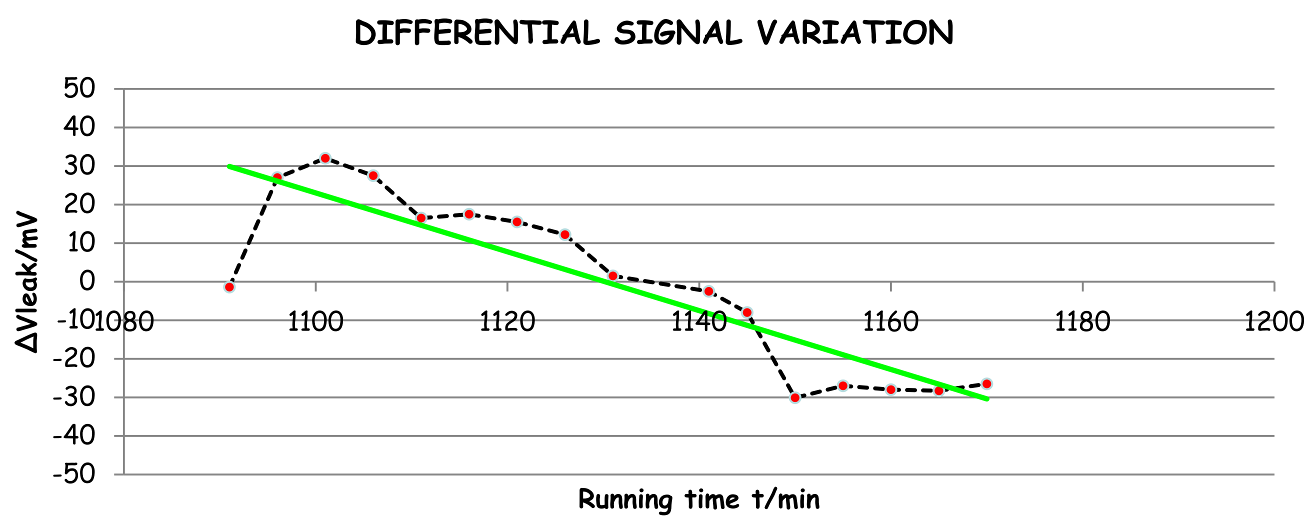
$Q_{L,IGLS} = 11 \pm 2(\text{stat.})$ mL/h

(measured recently by Givi)

Theoretically Feasible: $Q_{L,F} = 4 \pm 1$ mL/h

The source of the signal fluctuations in region (B)





In this LM2-M0 the interconnection pins were not still in their final-exact positions.
Let us assume a "Volume Expansion Strain", *c*, equal to 5:

$$c = \frac{\mathrm{d}V / V_0}{\mathrm{d}P / P_0} = 5$$

During the atmospheric pressure change we expect to have a rate of gas flow-out causing an increase of the mass flow in the outlet:

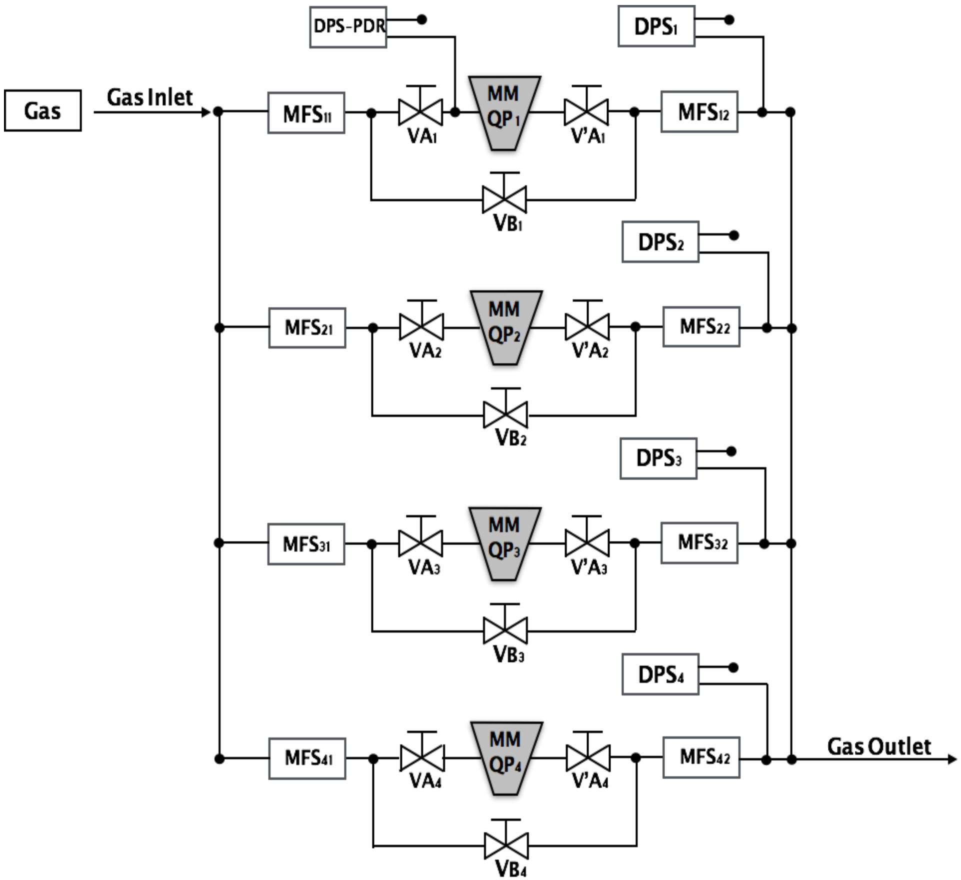
$$\delta V \approx 5 \frac{V_0}{P_0} \delta P \Rightarrow$$

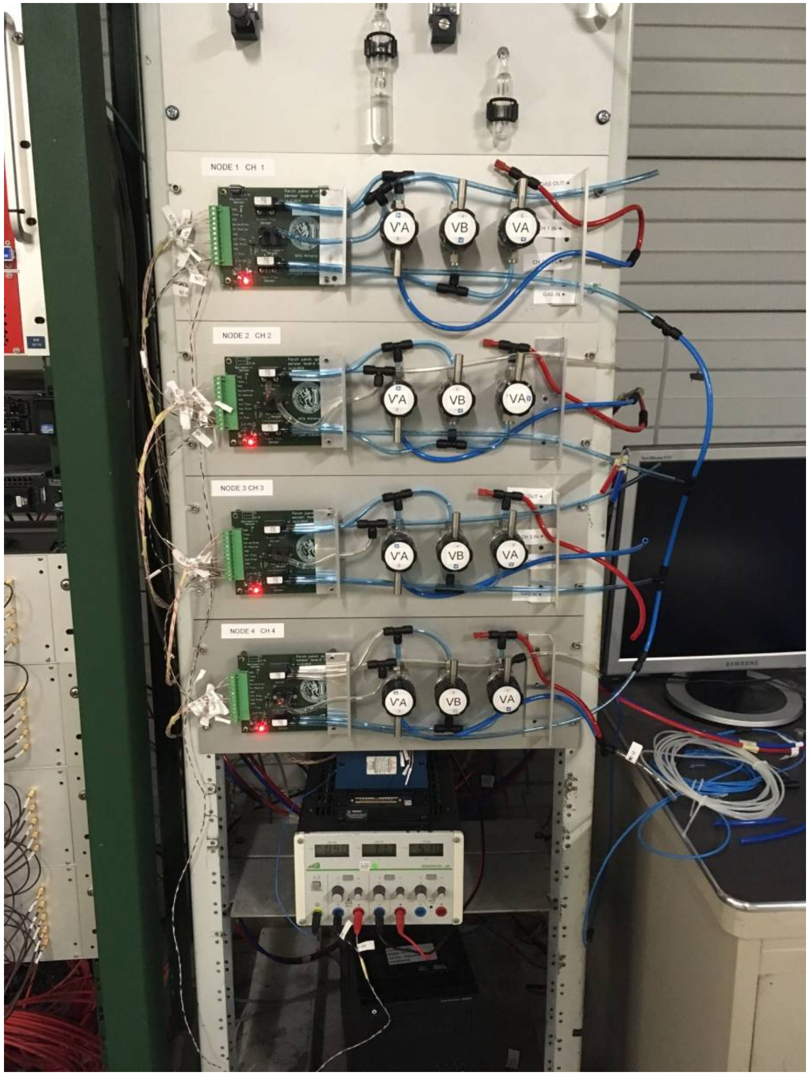
$$\text{for } \delta P = 1 \text{ mbar} :$$

$$\delta V \approx 0.32 \text{ L} \Rightarrow$$

$$\frac{\delta V}{\delta t} = \frac{0.32 \text{ L}}{1.33 \text{ h}} = 0.24 \text{ L/h}$$

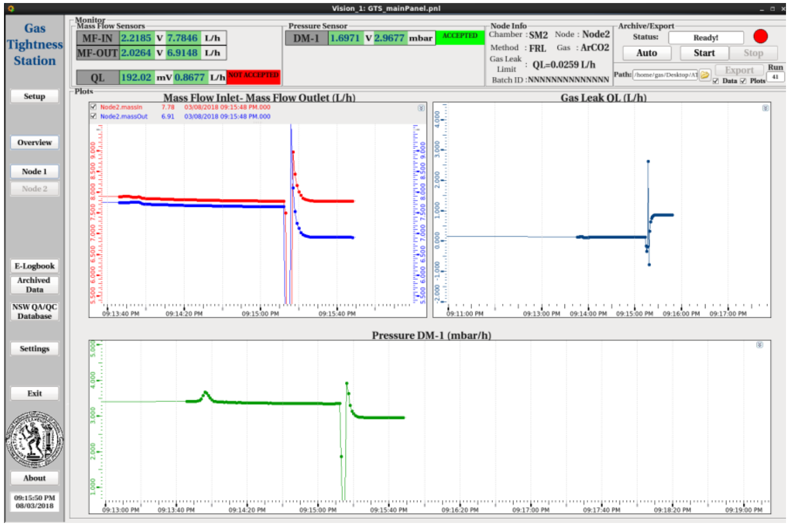
The source of the signal fluctuations in region (B)

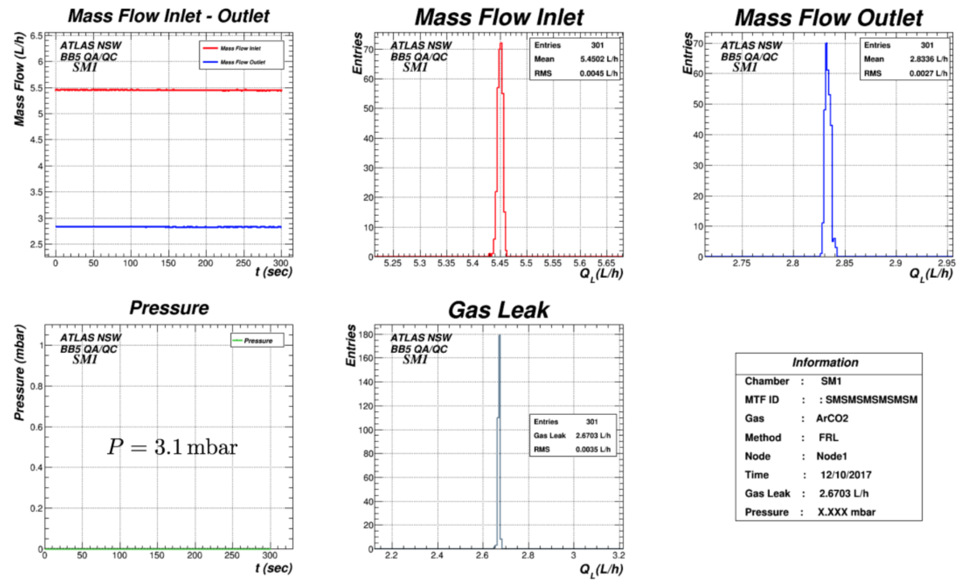




The Gas Tightness Station configuration (fully operational and stable) and can measure 4 Micromegas Quadruplets at the same time.

The Gas Tightness Station Control Software (WinCC)



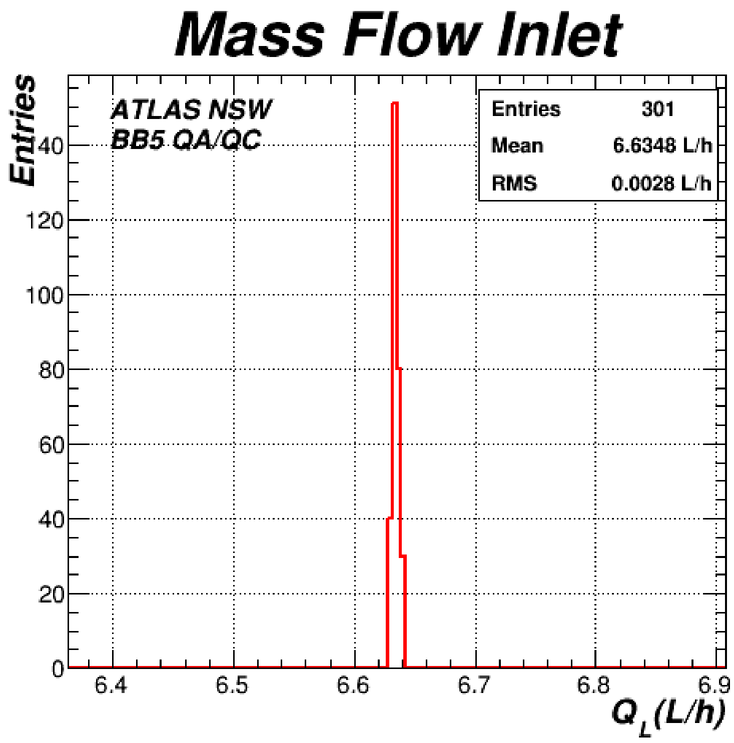


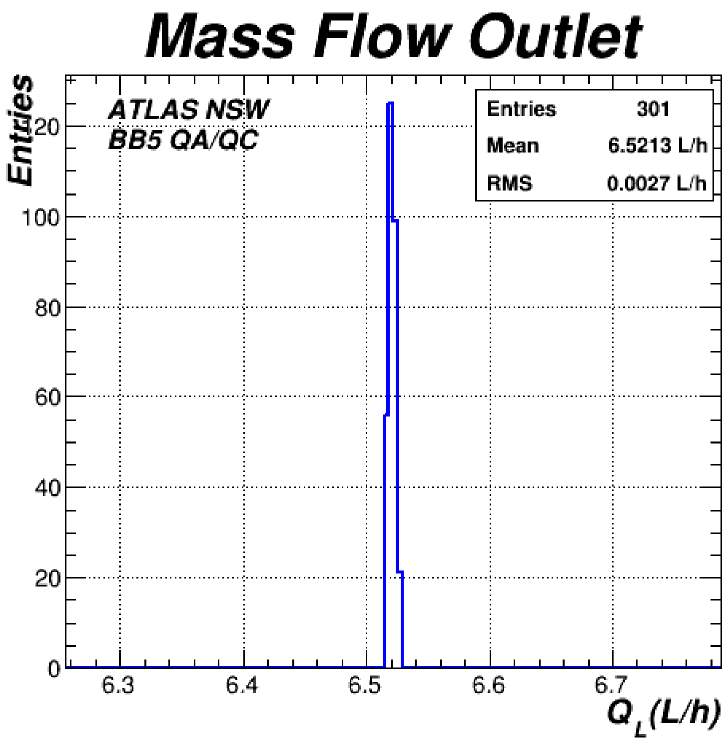
Written by using WinnCC-OA and covers:

- **FRL/PDR method for Air/Argon/Ar:CO_2**
- **Monitoring the MF sensors providing the flow rates and the leak rate**
- **Alarm handling for the leak rate and pressure of the MM QPs**
- **Access of data history of MM QPs (type or batch id)**
- **NSW Oracle DB (Freiburg GUI)**
- **Settings (calibration factors, offsets, gas type etc.)**
- **Automatic advanced analysis using ROOT**

(see Dipl. Thesis of P. Tzanis for more details)

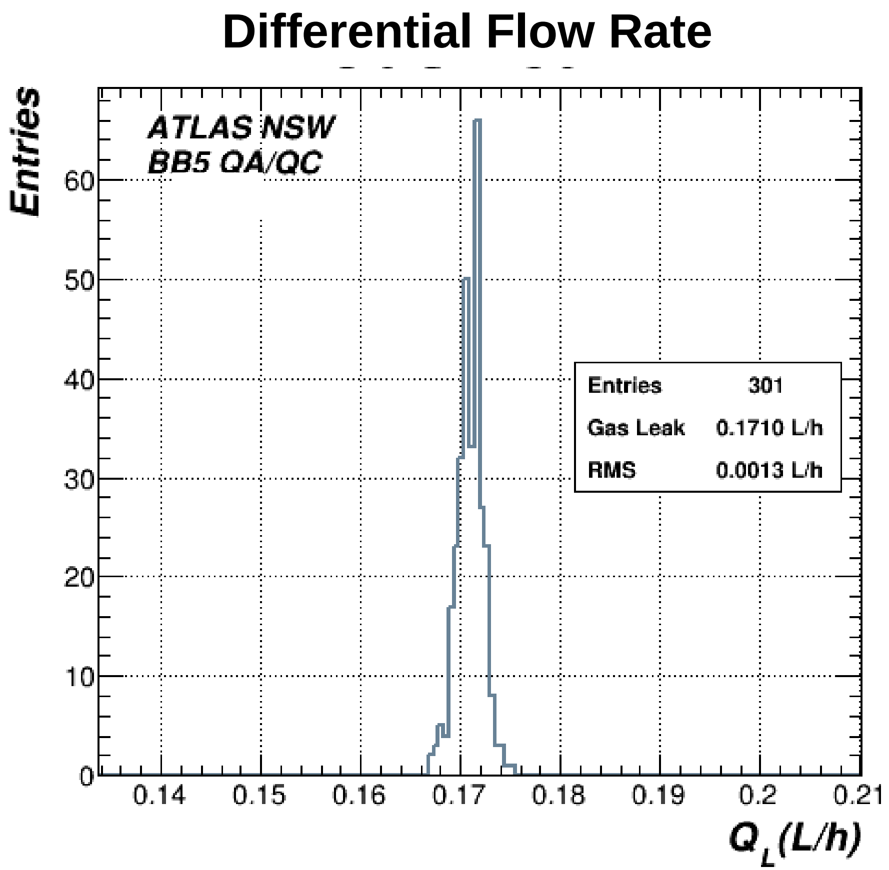
Study of the fluctuations (bypass mode)





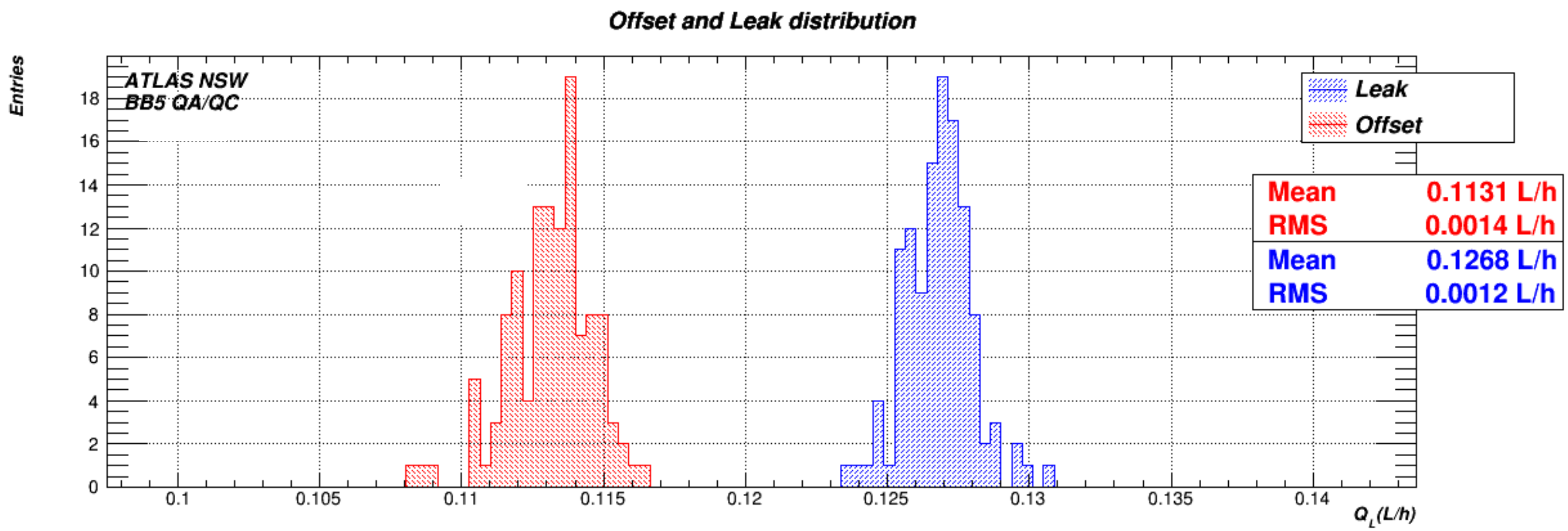
- **Flow rate distributions in by-pass mode (zero leakage)**
- **The fluctuations represent the MFS's repeatability.**
- **The RMS is 2.8 mL/h, including the systematic variations, but the output follows the input systematically.**

Obtained resolution



- **Differential flow rate (representing purely the fluctuations of the difference Qin-Qout) in bypass mode1.**
- **The RMS is 1.3 mL/h leading to a FWHM=3 mL/h, which is essentially the "detection limit" of the FRL setup.**

Advanced analysis of 32G needle leakage (D=105 μm)



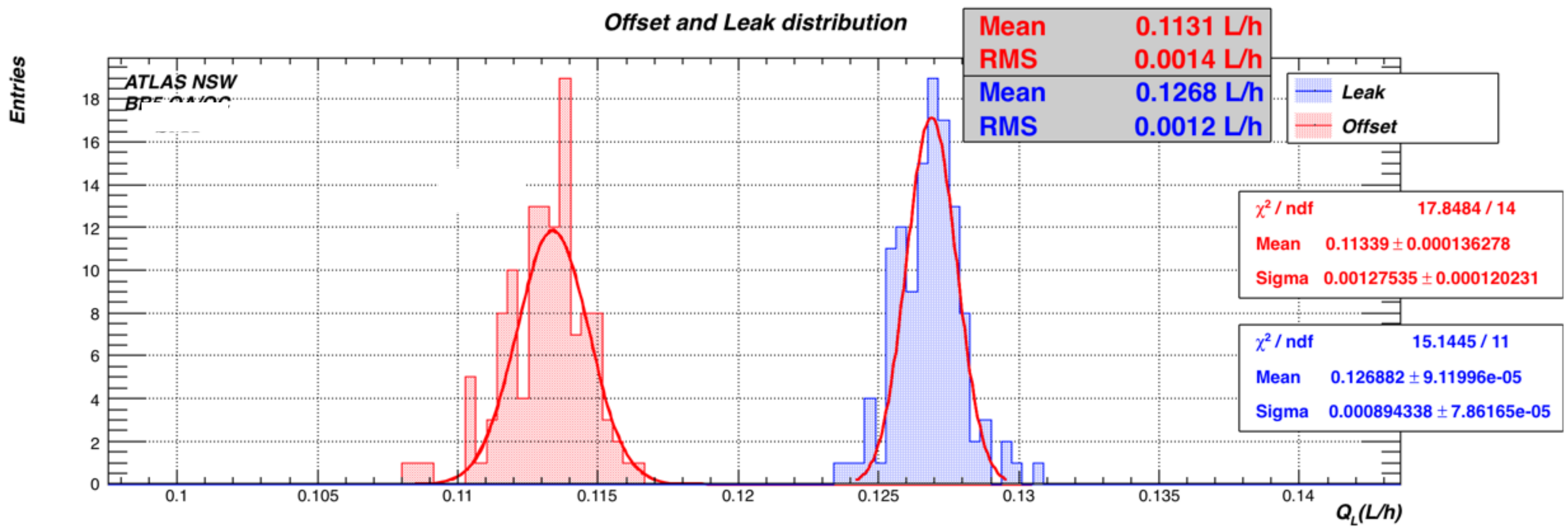
Leak rate Q_L=13.7 ± 1.7 (stat.) ± 0.7 (syst.) mL/h

Theoretical Feasible Sealing (TFS) of a LM QP $Q_{L,lim}$=4 ± 1 mL/h

Gas	:	ArCO2
Method	:	FRL
Node	:	Node1
Time	:	12/03/2018
Gas Leak	:	0.0137 L/h
Statistical Error	:	0.0017 L/h
Systematic Error	:	0.0007 L/h
Pressure	:	3.308 mbar

This leakage is about 1/3 the acceptance limit of a LM QP

Advanced analysis using double Gaussian fitting



Leak rate Q_L=13.5 ± 0.2 (stat.) ± 0.7 (syst.) mL/h

In case of measuring Q_L close the feasible leak rate limit of the MM QPs) the two Gaussians are expected to begin overlapping at about 1-sigma.

Conclusions

- The gas system of the NSW Micromegas Quadruplets has been designed according to the specifications
- We introduced end-to-end solutions for the specific gas components with optimal dimensions and low cost.
- A theoretical feasible sealing result has been calculated while we intoduced a novel gas tightness test method (FRL) which is going to be used not only in the BB5 (CERN) but at the costruction sides too.
- A setup for the gas leak test of 4 MM QP at the same time (M4-FRL), has been designed and now is fully operational and stable.