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The Quality Assurance-Quality Control of the Monitored Drift Tubes at the HEP Laboratory of National Technical University of Athens

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The description of the Quality Assurance and Quality Control (QA_QC) procedures for the Monitored Drift Tubes (MDT's) followed at the HEP Laboratory of NTUA are presented and results of the tested tubes are given. The MDT's are the elements from which muon chambers for the ATLAS/LHC Muon Spectrometer are built.

Introduction

The description of the Quality Assurance and Quality Control (QA_QC) procedures for the Monitored Drift Tubes (MDT's), which are built at the University of Athens, followed at the HEP Laboratory of NTUA are presented and the corresponding results of the tested tubes are given. The drift tubes which meet the specifications are used in order that the MDT chambers to be built at the University of Thessaloniki.

The quality assurance and quality check (QA_QC) tests performed at National Technical University of Athens are the following:

1. Wire tension measurement
2. Resistance measurement
3. High voltage leakage current measurement
4. Wire position measurement
5. Gas Leak rate measurement

The tubes that are approved and used for the construction of chambers must fulfil the following requirements [1]:

- A leak rate less than 10^{-8} bar $\times$ l / s.
- A wire location with respect to the centre of the reference surface of the end-plug less than 25 μm (corresponds to 2.5 the accepted r.m.s. of 10 μm displacement) in each transverse coordinate.
- A wire tension within ± 15 gf of the nominal value of 350 gf at the nominal temperature of 20 °C (corresponds to 2.5 σ with accepted σ = 6 gf).
- A leak current of 2 nA/m with High Voltage 3.4 kV and gas mixture Ar:CO_2 (93:7).

The wire tension is measured via the CAEN SY502 module [2] and a permanent magnet. The wire vibrates at the fundamental resonance frequency, which is measured and the tension force is calculated.

The HV leakage current, initially, was measured by a KEITHLEY 2000 multimeter and a KEITHLEY 614 electrometer, used as a voltmeter to measure the voltage drop across an 1 MΩ and finally 10 MΩ resistor in series with the tube, while the tube is supplied by the gas mixture Ar:CO_2 (93:7) at 3 bar absolute pressure and high tension of 3400 V (corresponding to a gas gain of 1.6×10^4). Presently an on line system with a good quality ADC is used.

The wire position is obtained via the ROME I - PAVIA electromagnetic micrometer (EMMI) [3], where inductive signals are measured on pairs of coils on both ends of the tube.

The gas leak rate measurement is performed by pressurising up to 50 tubes simultaneously with a gas mixture of Ar:CO_2 (93:7) at 3 bar absolute pressure. The gas leak rate test is based on the use of a differential manometer [4]. One of the two input lines of the differential manometer is connected to a reference tube (which has negligible leak rate) and the other to each one of the tubes to be tested. The system is inside a thermally isolated box and stays for 12 hours under pressure. The time of 12 hours corresponds to a kind of "relaxation" time of the system. After the relaxation time the initial pressure is measured, the vane of each tube is closed, and after 48 hours (typically) the pressure is measured for each tube and the pressure drop is estimated. We have two such boxes, hence we test 100 tubes simultaneously.

All the results of the tests are stored in a MS Access database and they are available at the NTUA home page.

1. Wire Tension measurement

The wire mechanical tension has to be known with enough accuracy in order that the position of the wire in the region between the wire locators to be calculated. This is done, by estimating the gravitational sag of the wire, based on the measurement of the mechanical tension. The wire tension of the tube is measured with a wire stretch meter provided by CAEN (type SY502) (see Figure 1).

The principle of operation is the following. The tube wire is excited by a square current pulse (see Figure 2). The middle (of a length of 10 cm approximately) of the tube (and the wire) is located inside a magnetic field produced by a permanent magnet. The magnetic force makes the wire to vibrate. The wire vibration inside the magnetic field produces an induced electromagnetic force on the wire, which is detected by the stretch meter. A feedback mechanism keeps the wire in sustained oscillations. Because the excitation takes place in the middle of the wire, the fundamental frequency dominates, even though the displacement versus time is not a harmonic function (see Figure 3). The meter measures the fundamental frequency of the sustained oscillations (i.e. the fundamental frequency of the free vibration). The microprocessor of the stretch meter determines the wire mechanical tension (F) from the oscillation frequency (f) of the ground mode wire vibration, based on the expression:

$$F = \pi \rho d^2 L^2 f^2 \qquad \text{(in S.I.)}$$

The following data is input to the CAEN module: the wire length (L=165 cm), the wire diameter (d=50 μm) and the density (ρ=19.3 g/cm^3) of the wire material (gold plated W-Rh). This measures the frequency, processes all this information and calculates the wire mechanical tension. The CAEN module is connected to a PC and controlled by LabVIEW through an RS232 connection. The calculation of F is done within the LabVIEW programme, based on the above input data, with more significant digits than the meter accepts. It is worth mentioning that the accuracy with which the wire data are known is not very good, d = (50 ± 5) μm, so it is better to refer to the vibration frequency too.

The magnetic field is provided by a permanent magnet (55 × 45 × 60 mm^3) made by Alcomex (CERN scem 08.14.01.340.4).

The set-up of the wire tension meter (magnet and CAEN module) has been checked and verified in two ways. First, a horizontal stand was used to stretch an anode wire of 165 cm length. A weight of exactly 350 gf was used for this purpose. A series of measurements were taken by adding additional exact weights of 50 gf and 100 gf. The wire tension measurements with the CAEN module and the magnet, agree with the applied weight within an error of less than 1 %.

Secondly, the frequency of the vibrating wire was measured using a LeCroy 9314AM digital oscilloscope and was compared with the one measured by the CAEN module. The agreement is better than 0.5 %.

The required wire tension of the tube must be kept within a tolerance of ± 5 % of the nominal value of 350 gf, at the nominal temperature of (20 ± 1) °C (the wire ground mode frequency has to stay within ± 2.5 % of the nominal value). During the tension measurements the tube temperature is controlled and measured with this accuracy. The mechanical tension varies as temperature changes by 1.5 gf/K (see Appendix I). Measurements are presented in Figure 4.

When we first got the SY502 module we noticed that the measurements were systematically lower than what was expected. We measured the frequency with the LeCroy oscilloscope and compared it to what the meter was measuring. The meter's frequency was consistently lower by approximately 2 %. The problem was found to be related to the 100 kHz frequency produced by the meter (see Fig. 5), which is used to measure the frequency of vibration. This frequency is produced by the U14 IC (the 74LS221) that contains two monostable multi-vibrators. The frequency can be adjusted with the use of the *R*49 1 kΩ variable resistor. We used a square pulser made 'in-house' that produces signals as small as 10 mV with an accurate frequency of 50 Hz (crystal accuracy a few per million). We 'fooled' the meter by connecting its input to the above signal and the meter measured the 50 Hz frequency. We adjusted *R*49 until the meter registered the expected 50 Hz. In order to do this we had to replace the *R*50 1% 6.2 kΩ resistor with one slightly larger. Another problem was that sometimes the meter did not start measuring. We had to replace both U14 and U15 (U15 is the same IC as the U14). We then had to readjust *R*49. For more than a year now, after the final adjustment, we measure from time to time the above frequency of 50 Hz and have found that it is extremely stable at the level of 1 per thousand.

We noticed that by using a higher magnetic field the measurement gives larger frequency and wire tension. For *B* fields of 430 gauss (43 mT) and 2000 gauss (200 mT), the same wire gives 351 gf and 356 gf respectively. This is probably due to larger amplitude vibrations of the wire that leads to non-linear effects.

Indeed by doing the analysis for vibrating string without the usual approximations for small vibration amplitude, the following expression is found

$$\frac{\partial^2 z}{\partial t^2} = \left(\frac{\sigma_0}{\rho_0}\right) \frac{1 + \frac{Y}{\sigma_0}\left(\sqrt{1 + \left(\frac{\partial z}{\partial x}\right)^2} - 1\right)}{\left(1 + \left(\frac{\partial z}{\partial x}\right)^2\right)^{3/2}} \frac{\partial^2 z}{\partial x^2} \ ,$$

where Y is Young's modulus, σ_0 is force per cross sectional area of the wire, ρ_0 is the volume density of the wire, z is the transverse displacement of the wire and x is the coordinate along the wire. If one ignores the first partial derivatives gets the usual wave equation with constant speed

$$u_0 = \sqrt{\frac{\sigma_0}{\rho_0}} = \sqrt{\frac{F}{\rho_l}} \ ,$$

where F is the mechanical tension of the wire and ρ_l the mass density per unit length.

In the present non linear case one can identify an average speed equal to the average of the expression in front of the second partial derivative of the second member of the above wave equation. One can easily find, to a first approximation, that this gives an average speed greater than the u_0, and agrees qualitatively with our measurements.
Sometimes the wire vibrates at the 3^{rd} harmonic. One can make it vibrate at the 1^{st} harmonic by moving the tube, and by slightly tapping the tube by hand.

The average time per tube measurement is 1 min.

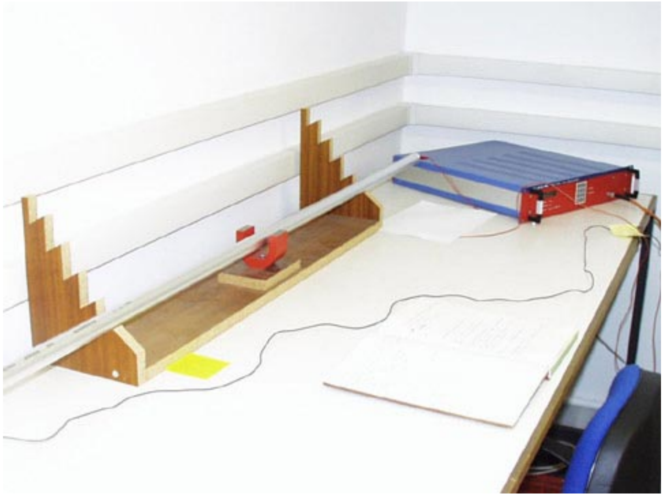


Figure 1. The mechanical tension measuring system.

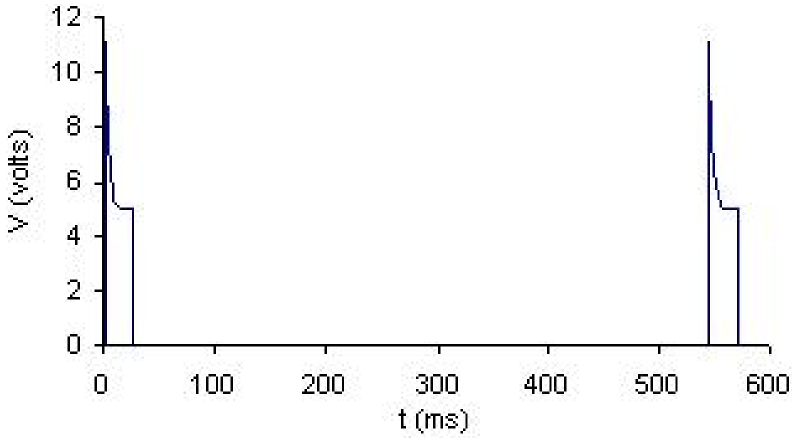


Figure 2. Initial excitation pulses from the CAEN SY502 module, observed by an 1 MΩ input scope. Pulse width is approximately 27 ms and the period is 545 ms.

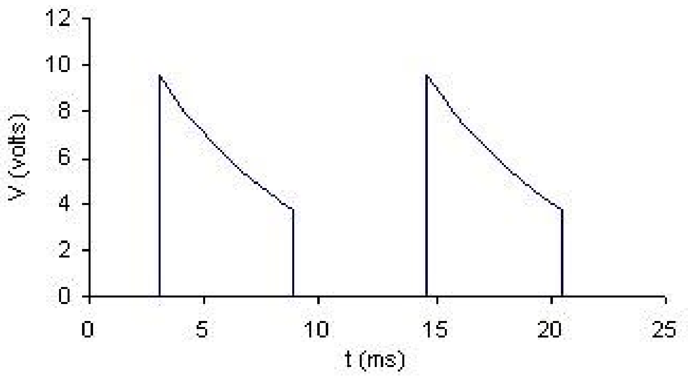


Figure 3. The pulses at the wire ends during sustained vibrations, observed by an 1 MΩ input scope.

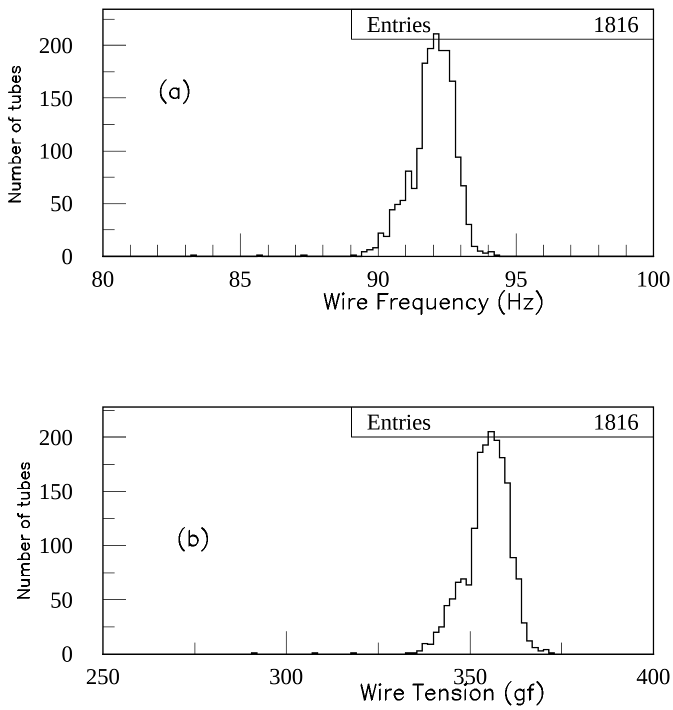


Figure 4: Wire tension measurements.

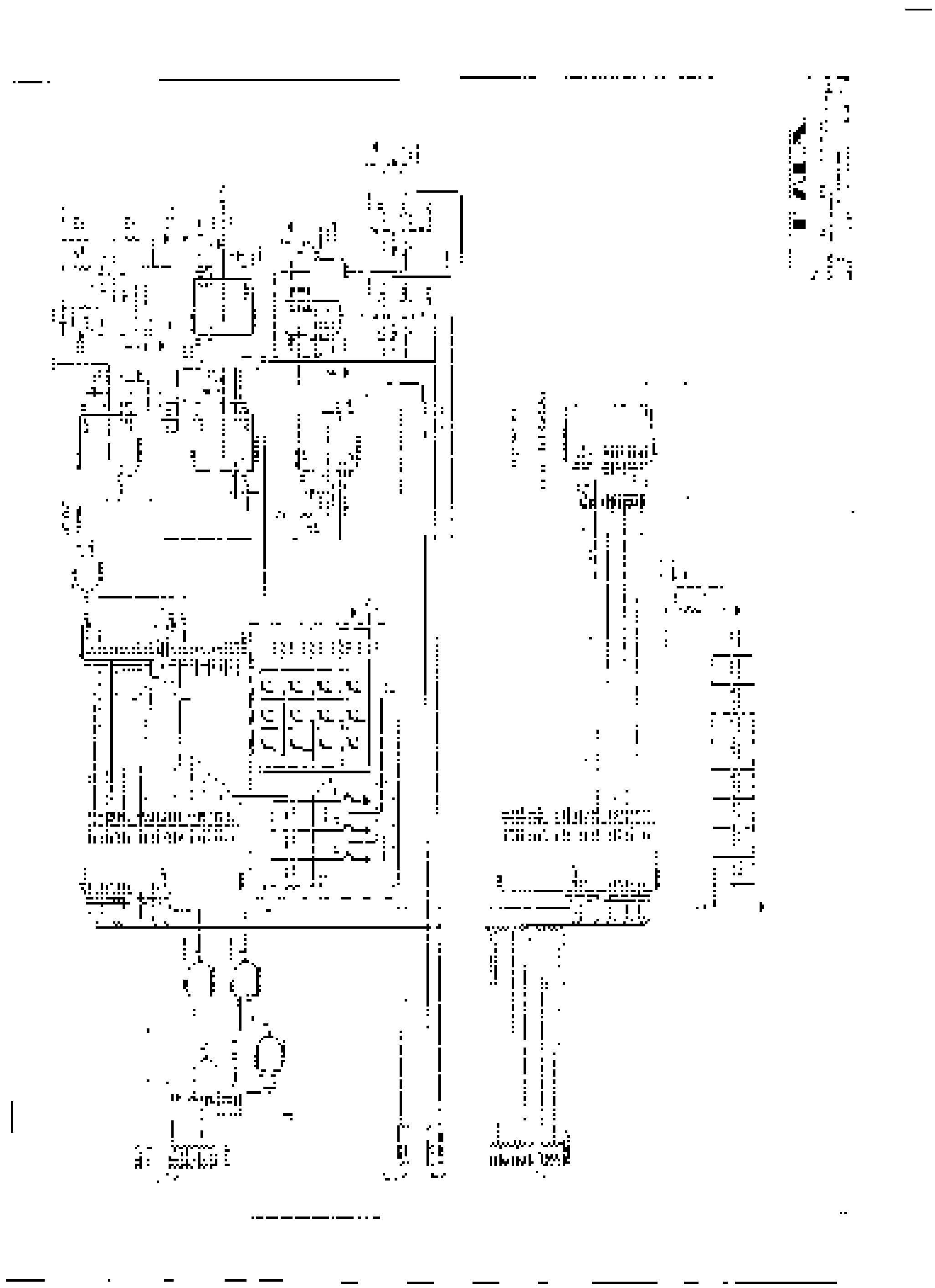


Figure 5: Block diagram of CAEN module SY502.

2. Resistance measurement

The purpose of this measurement is to test the electrical connection between the tube end-plug and the cylinder, and use the result for comparison with similar measurements after sometime, in order to see if there is any deterioration in the conduction due to corrosion effects.

The resistance measurement is based on the application of Ohm’s law. We applied an 1 A, dc current, through the tube, between the two end-plugs. We measured the voltage drop across the ends of the two end-plugs. The values obtained are much lower than the acceptable value of 100 mΩ. Obtained data are presented in Figure 6, corrected for various values of resistance (the tube resistance of 0.6 mΩ and the resistance arising from the imperfections of the contact of the wires with the end-plugs, which is of the order of 2 mΩ to 4 mΩ). The method gives the sum of the resistance for both end-plugs. After some initial measurements this test is not performed anymore.

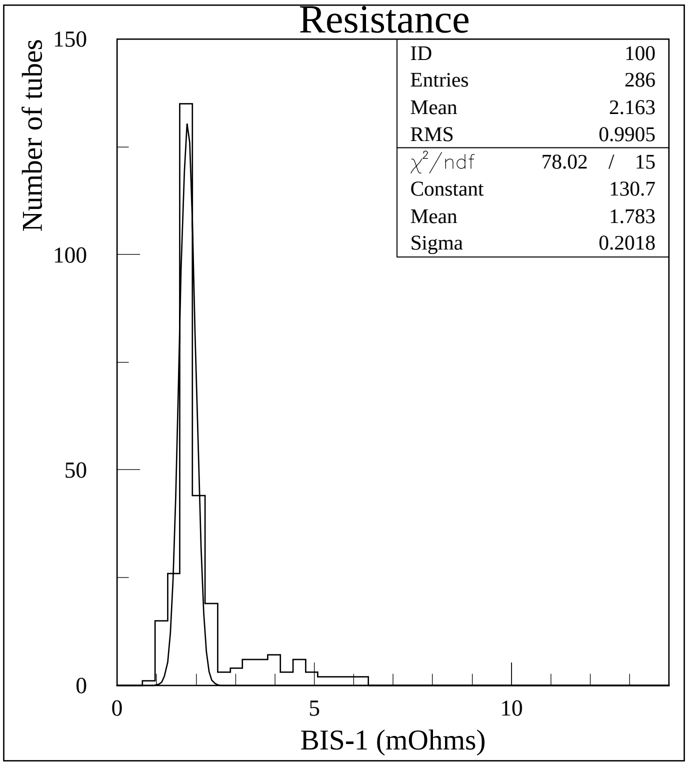


Figure 6 : Results of resistance measurements.

3. HV Leakage Current measurement

The HV leakage current is measured as follows. The tube is filled with the gas mixture Ar:CO_2 (93:7) at three bar pressure (absolute), and then HV is applied up to 3400 V (gas gain 16×10^4). The circuit, which has been used for our measurements is shown in Figure 7. At the beginning, we measured the voltage drop across a resistor of 1 MΩ, and later 10 MΩ, connected in parallel with an electrometer, namely Keithley 614 or the multimeter Keithley 2000. Both have low input offset currents and can measure voltages from a source with high resistance. The resistor was connected at the side of the ground wire.

The use of the ground-side has the advantage that one can easily use a PC with an ADC card of good quality to measure many tubes simultaneously. Presently we use such a card for our measurements. Another factor is safety, and the third is the fact that if one uses a voltmeter that gets power from the mains, it cannot have any of its probe wires with more than 500 V from ground. With the 10 MΩ resistor, 0.1 mV voltage drop corresponds to 1 nA current through the resistor.

. Measurements of HV leakage currents are presented in Figure 8. The tubes with large leak currents are put in reversed voltage for tens of minutes. This procedure cures the great majority of "bad" tubes.

Each tube measurement lasts 1.5 min on the average (for 2 persons).

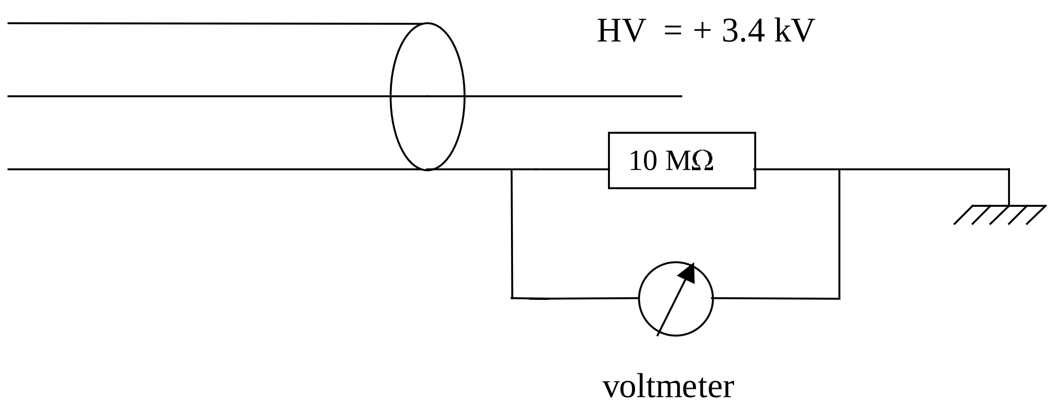


Figure 7 : The circuit for the leakage current measurements.

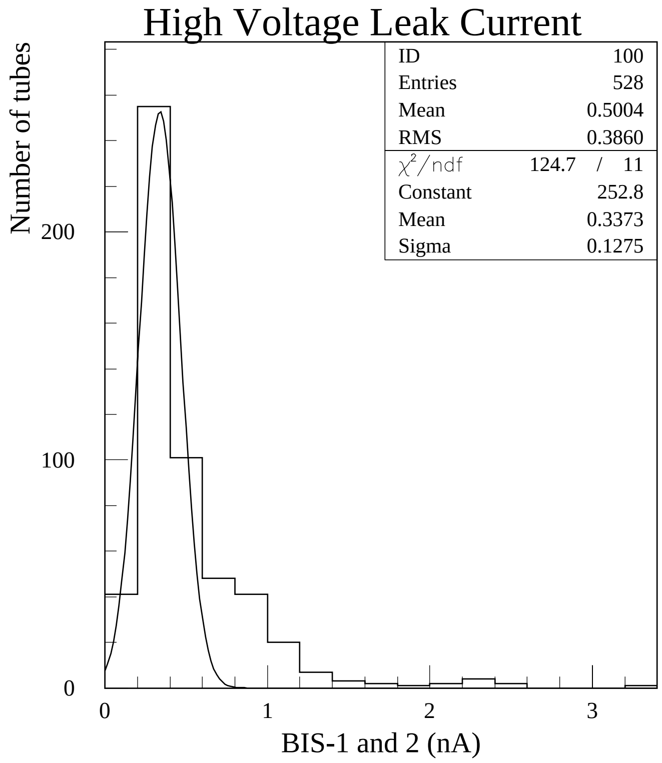


Figure 8 : HV leakage current measurements.

4. Wire position measurement

An important parameter for the muon spectrometer is the accuracy of the location of each wire with respect to the tube axis. The wires have to be located at a distance of less than or equal to 25 microns from the tube axis in two orthogonal and transverse to the tube directions (corresponds to 2.5 standard deviations of 10 μm). The ROME I - PAVIA electromagnetic micrometer (EMMI) is used for this purpose.

The operation principle is the following. An alternating current $i(t) = i_0 \cos \omega t$ is run through the tube wire. Let the wire be at a distance L-d and L+d respectively, from the middle of each one of two coils of surface α×b (see Figure 9). The electromotive force (emf), $\mathcal{E}$, induced in each coil is:

$$\mathcal{E} = na\mu_0 i_0 f \ \ln\left(\frac{L \pm d + \frac{b}{2}}{L \pm d - \frac{b}{2}}\right),$$

where n is the number of coil turns. We connect the coils in series in such a way that we get the difference of their emf's. We assume that the coils are identical and we get the following result for the total emf:

$$\Delta\mathcal{E} = n\mu_0 i_0 fa \ln\left(1 + \frac{2db}{L^2 - \left(d + \frac{b}{2}\right)^2}\right)\sin\omega t = \Delta\mathcal{E}_0 \sin\omega t$$

The above formula gives a very good linear relation between the displacement *d* and the induced total emf for relatively large displacements. The induced signals are very small and buried in noise. To be able to get the signal, the lock-in technique is used. The system is shown in Figure 10.

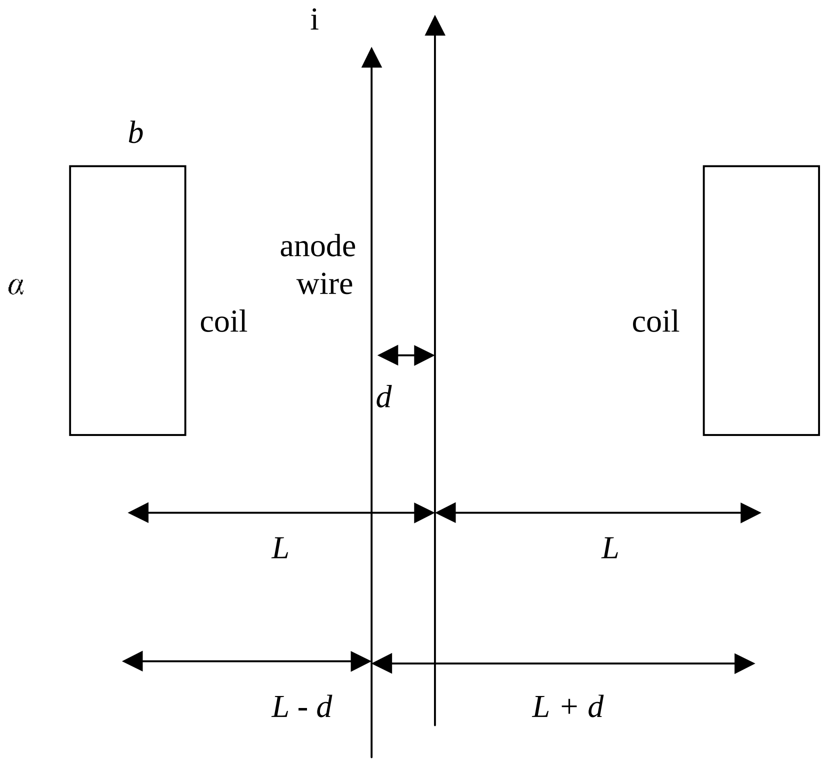
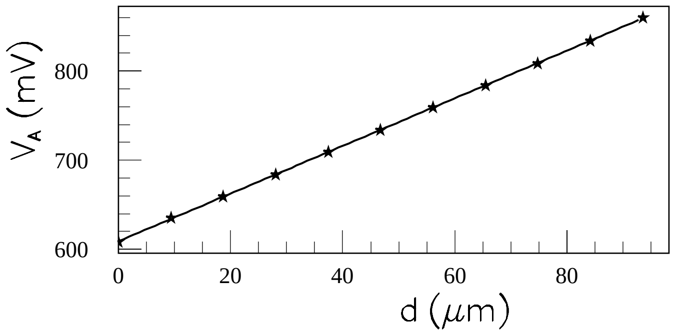


Figure 9: The principle of wire position measurement with the use of EMMI.

Figure 10: The EMMI system, the tube V-shape support and the coils.

The EMMI device consists of:

- Two fixed V-blocks, on which the tube end-plug precision surfaces are supported.
- Two pairs of movable coils, near the V-blocks.
- A signal generation board, which provides the tube wire with an oscillating current.
- Two read-out boards, which read out the signals induced on the coils.



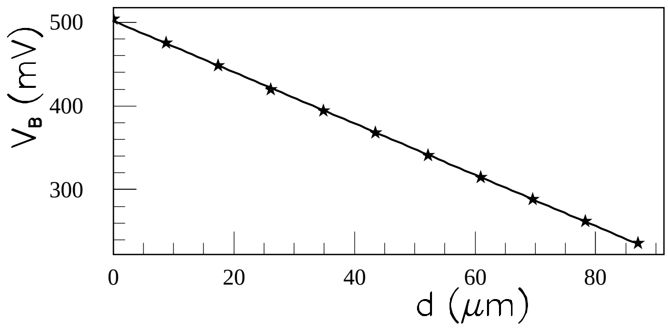


Figure 11 : Voltage versus displacement measurements for side 1 (A) and side 2 (B) respectively.

During the measurement procedure, the tube is placed on the two V-shaped precision supports between the coils and it is rotated around the endplug axis. The output which is proportional to the magnitude of the total emf is recorded for 4 equidistant angular positions (0°, 90°, 180°, 270°). The wire offset is calculated from the above measurements and the calibration measurements. The wire displacement is found with an accuracy of 2 microns.

The output voltages are read with voltmeters and transferred through an ADC card to a PC using a LabVIEW code. The results are saved to the data-base.

The electronic part of the EMMI set-up (signal generation board and read-out board) had to be adjusted by us in order that to have it work properly.

A position calibration factor, which relates the measured signal in mV and the displacement of the wire in microns, is needed. This factor has been obtained with the help of two mechanical gauges (MITUYOMO dial indicator), a dial indicator device mounted to each coil. These devices give us the capability to change the position of the coils relatively to the position of the tube wire. Taking measurements at twenty different positions we find the position calibration factors for each end of the tube in mV/μm (2.67 mV/μm for side 1 and 3.07 mV/μm for side 2). The results are presented in Figure 11.

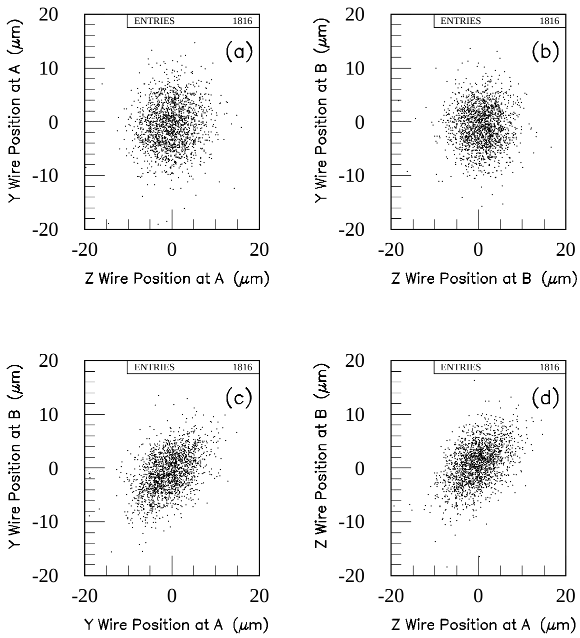


Figure 12: Wire position measurements for the transverse *z* and *y* coordinates and the radial shift r from the axis for the two ends of each tube z_1, y_1, r_1 and z_2, y_2,r_2 respectively. The number 1 indicates the site which has the tube stop, where the numbers and letters on the tube are marked .

We found that the two MITUYOMO dial indicators (micrometers) were not accurate enough. We used calibration gauges (plates) and compared the displacements of the two meters for plates of real 50 μm and 100 μm. One of the micrometers gives, for the case of real 100 μm, 107 μm and the other 115 μm. We corrected for this offset.

Our EMMI system has a pair of teflon (electric insulation) balls in each V-block, on which the precision surface of the end plug of the tube rests. The tube is electrically insulated from ground. At one end of the tube there was an aluminum end stop. We observed instabilities in the system due to the fact that sometimes we had good conduction with the aluminum stop, which is connected to the ground, and sometimes we had not. We replaced the stop with a plexiglass one (insulating) and the instability disappeared. The system is very robust as long as there is no change in the metallic surroundings of the system, during the whole set of measurements for each tube. Even though the values of the voltages change when the surroundings change, for different but constant surroundings the relative values are not affected. One gets, for example, the same voltage differences for the same displacements. We tested the effect of Eddy currents on the measurements. Note that Eddy currents produce signals 90^0 out of phase relative to the real (initial) signals and because of that, their effect is reduced due to the way the lock-in technique works as long as the system is well adjusted.

We did the following tests: We used a wire without a tube and measured the displacement versus voltage and then estimated the calibration constants. We found that the calibration constants for the two respective ends were the same with the ones for the case of the tube, within an error of less than 1%.

Another measurement was done as follows. A wire was fixed and a tube without end-plugs surrounds it. The tube was fixed to the coils. The tube with the coils, were displaced and the calibration constant was measured. The new constants were the same as with the normal case of the tube, with an error of the order of 2% to 3%. All these lead to the conclusion that for our system no correction for Eddy current effects is needed. We tested our system for consistency of the two pairs of coils. We used several tubes and measured each of their ends with the two different coil pairs. The results obtained differed in all cases by less than 1.2 μm.

The wire position measurement per tube takes on the average 1 min.

Results for the wire position measurement are presented in Figure 12.

5. Gas Leak rate measurement

The experimental setup, we developed, allows for the measurement of the average gas leak rate through the whole body of the tube (end-plugs and cylindrical surface). The method used is a differential manometer method, which uses non- leaking tube as a reference.

The formula that gives quantity the *L*, which is actually a measure of the real gas leak rate (even though it is used with the name "gas leak rate") is

$$L = V \frac{\Delta p}{t}$$

where $$\Delta p = \frac{V}{t}\left(\frac{T}{T^i} p^i - p\right) \qquad (1)$$

The details of the method are described in Appendix II. The basic idea is to measure (estimate) correctly the pressure drop due to gas leakage at the time interval *t*. *V* is the volume of the "leaking" tube and Δp is the pressure drop corrected appropriately.

This method is sensitive to the temperature stability and uniformity along the measuring tubes and the reference tube. For this reason specific thermally insulated boxes have been constructed to enclose the system of tubes.

The tubes to be tested are put inside two very similar such boxes. The first (A) is made entirely from wood, while the second (B) from metallic frame with wooden walls. The walls are covered by a thermal insulation material, of thickness of 10 mm and thermal conductivity λ=0.038 W/(m K) (DIN 52612). The thermal loss coefficient of the insulation material is $k=\lambda/d$=3.8 W/(m^2 K), while the overall effective k of the walls is estimated to be 2.9 W/(m^2 K). The low period variations of the room temperature are smoothened satisfactorily inside the box. From our test measurements, we found that the temperature variations in the air-conditioned room with a time period of 1 h, are reduced by a factor of 5 inside the box.

We put 50 tubes inside each box, which are arranged in two layers (lower and upper) and are connected in the manifolds in groups of 5 pieces. The gas leak system is located in the HEP Laboratory, where the temperature is stabilized within ± 1 ^{o}C by the operation of an air conditioner. In Figure 13 an operational diagram is shown, while Figure 14 shows a general view of the whole system.

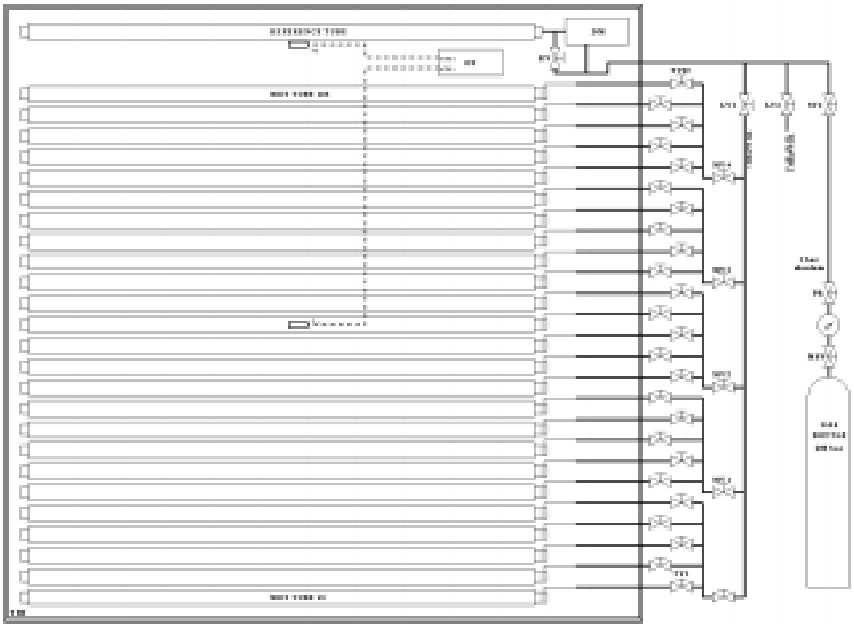


Figure 13 : A schematic diagram of the experimental setup for the MDT gas leak rate measurements. DM: differential manometer; DT: Dual thermometer; TV: Tube vane; MVi: Manifold vane; LVi: Line vane; RV: Reference vane; MSV: Main supply vane; PR: Pressure reducer.

Groups of 5 tubes are connected to the corresponding manifold, which is also connected to the main gas supply line. The reference line of the differential manometer (DM), type FDD from Sensotec, is connected to a reference tube having the same dimensions with the MDT's. The measuring line of the DM is connected to each tube sequentially using the corresponding vane. A dual thermometer (DT) from Bioblock Scientific, with Pt100 sensors and an accuracy of 0.01 ^{o}C, is used to record the temperature in the middle of the system and in the reference tube as well. An additional thermometer from Vaisala with an accuracy of 0.03 ^{o}C is used to record the room temperature.

The tubes are filled with the detector gas (Ar:93 %, CO_2:7 %), which is supplied from a bottle via a pressure reducer. The pressure applied is 2 bar relative to the atmospheric air pressure (3 bar absolute). Specific, low leakage vanes (LLV), type HP 200 IM from Air Liquide, are used to avoid a leakage causing an extra systematic error. These vanes have an extremely low leakage between the inlet, outlet and its body, which is less than 10^{-12} bar × l/s with Helium, as stated by the manufacturer. The DM has a full range of 0 to 5 PSID (344.75 mbar), giving a voltage analog output in the range 0-5 V. The gas leak test is performed following three main steps described below.

Figure 14 : Views of the thermally insulated box from inside and outside. Each vane is connected with the corresponding MDT detector in the box via a twisted narrower tube.

- Tube installation and gas filling: The tubes being tested and the reference tube are filled with the gas mixture, at 3 bar. The system is kept in this state for a transient time of at least 12 h. In this way temperature and general system stabilization is obtained. It is probable that there are transient phenomena like gas leaking inside the micro-cavities of the end-caps.
- Starting the leak test: The reference vane is closed while all the initial temperatures are recorded. After that, all the tube vanes are closed in sequence.
- Measurement of the pressure drop: Approximately 48 hours after the second step, the differential pressures between the manifold and each tube are recorded before and after opening the tube vanes.

On-line monitoring

An on-line monitoring program on a PC has been developed to control the experimental procedure of the gas leak test. We used the LabVIEW environment to develop a specific "VI" program for this test. The parameters, which are recorded during the measurement procedure are, the temperatures from the two sensors and the differential pressure from the DM. A 12-bit/16-channel ADC from National Instruments (type PC-LPM-16) is installed on the PC and it is used for reading the differential pressure. The two temperature values are recorded directly in digital form connecting the PC with the thermometer by RS-232. Thus, we exploit the high accuracy of the thermometer avoiding effects from A/D conversion.

In the control panel of the program the sampling number and period can be selected, depending on the total time interval. The evolution of the gas leak test is monitored by using a factor,

$$F_T = 1 - \frac{T T_r^i}{T^i T_r} \qquad (2)$$

F_T indicates the degree of the variation of the temperature conditions (see Appendix II).

The appropriate measuring time is selected such that the above factor is maintained within narrow limits and preferably close to zero, minimizing the systematic error.

The volume V of the MDT's, in our case, is 1.1 L. The "active" length of the tube is 165 cm and its diameter D=29.2 mm.

A correction has to be applied to the measured differential pressure due to the possible influence of the non zero volume of the manifold. According to the ideal gas law, this correction is:

$$\Delta p' = (1+a)\Delta p'' - a\Delta p'_m = \Delta p'' + a(\Delta p'' - \Delta p'_m)$$

where $\Delta p''$ is the differential pressure of the system (tube + manifold), $\Delta p'_m$ is the differential pressure of the manifold, a is the ratio V_m/V, where V, V_m are the volume of the tube and the manifold respectively.

A typical value for V_m is 0.04 L, which is about 1/30 of the tube volume, so $a \approx 0.033$. The pressure in the manifolds usually differs from that of the tube under test by less than 2 mbar. This corresponds to a term $a(\Delta p' - \Delta p'_m) \approx 0.07$, which leads to a relative correction of the order of 2 % of the nominal value of gas leak (10^{-8} bar $\times$ l/s).

Error estimate

In the calculation of the pressure drop, the overall statistical error can be estimated as follows:

$$\delta\Delta p = \sqrt{(\Delta p' \frac{\delta T^i}{T})^2 + (\frac{T^i}{T}\delta\Delta p')^2 + [\delta(p_r F_T)]^2} \qquad (3)$$

The term $p_r F_T$ can be calculated from the known F_T and considering $p_r \approx 3$ bar. Its variation can be recorded during the measurement of the tubes. In our system, we use only three temperature sensors, the first two located in the vicinity of the central region of each layer and the third in contact with the reference tube. The statistical fluctuations of F_T have to be within an allowed practical range (i.e. $\pm3\times10^{-4}$ in the worst case). As mentioned above, the term p_rF_T expresses a systematic error of the measurement of the differential pressure drop. Due to the finite time duration of the pressure recording, while opening the vanes at the end of the measurement procedure, this term appears to have certain variation. Thus, in the calculation of the overall error of Δp, we consider the partial contribution of the variation of the term p_rF_T, that is $[\delta(p_rF_T)]^2=2\sigma_T^2$. Substituting in Eq. 3 we obtain:

$$\delta\Delta p = \sqrt{(\Delta p'\frac{\delta T^i}{T})^2 + (\frac{T^i}{T}\delta\Delta p')^2 + 2\sigma_T{}^2}$$

From our measurements during the test, we observed that the factor F_T has values in the maximum range of $(1\text{-}1.5)\times10^{-4}$ to $(1+1.5)\times10^{-4}$. It can be shown that this value corresponds to a variation of the temperature difference, T_t-T_r, of about 0.025 ^{o}C. The temperature variations across the tube array measured systematically and were of this order. Hence we conclude that $F_T=1.5\times10^{-4}$ and $\sigma_T=0.70$ mbar.

The absolute error of the differential manometer is 0.1% of the full scale, that is $\delta\Delta p'=0.35$ mbar.

The thermometer used is very accurate ($\delta T=0.01$ ^{o}C). For the value of $\Delta p'$ we have $\Delta p' \approx 1.55$ mbar (for time intervals of 2 days), hence the first term $(\Delta p'\delta T^i/T)^2$, is negligible compared to the other two terms (typical values of the two terms are, 2.7×10^{-9} mbar^2, 0.12 mbar^2 and 0.20 mbar^2 respectively). We conclude that the absolute statistical error is $\delta\Delta p' \approx 0.56$ mbar (the relative error is $\delta\Delta p/\Delta p'=0.56/1.55=0.36$).

As a result, the overall statistical error of the leak rate is given by :

$$\delta L = \frac{V}{\Delta t}\sqrt{(\frac{T^i}{T}\delta\Delta p')^2 + \sigma_T{}^2}$$

A typical value is $\delta L \approx 0.36\times10^{-8}$ bar$\times$l/s, that is ≈ 36 % in respect to the nominal leak rate. It is obvious, that the main contribution to the error of L, comes mainly from the second term expressing the variation of the temperature difference.

Compensation against the temperature variation

Trying to reduce the time interval of the gas leak test, i.e. to complete it in 1 or 2 days, the compensation of the systematic error, caused by the temperature effects, is quite necessary. This compensation can be performed calculating the term P_rF_T according to Eq. 2. In this correction, we have to assume that the temperature uniformity is maintained sufficiently well along the particular tube layer.

Another, auto-compensation technique is used based on the idea of using "test tubes" in thermal contact with the tubes under test having a given leak-rate (either accurately measured before in a longer time interval or very tight, so there is practically no leak). In this configuration, the temperature conditions in the "test tubes" are, in principle, very similar to those of the tested tube. Recent results have shown that such a method gives corrections, which seem very reliable. The compensation can be done in the off-line analysis calculating the obtained net pressure variation apart from the expected pressure drop value, according to the following formula

$$\Delta p_c = (L_m - L_o)\frac{\Delta t}{V} \ ,$$

where Δp_c is the compensation term, L_m is the measured leak-rate and L_o is the leak-rate which is very well known (it is nearly zero when very tight tubes are used). The resulting pressure drop Δp is given by adding the compensation term,

$$\Delta p \approx \Delta p' + \Delta p_c$$

The experimentally measured values of Δp_c are mostly within the range of -0.45 to 0.45 mbar, depending on the temperature conditions. Considering the nominal leak-rate of the BIS MDT's (1×10^{-8} bar x l/s), the corresponding pressure drop rate is 0.777 mbar per day, a value, which could be affected by the temperature effects during a day, leading to a systematic error. The compensation techniques described are used for cross checking to prevent erroneous acceptances or rejections of the tested MDT's.

Absolute calibration

As discussed above, the leak rate is referred to the reference tube, which is very tight. The absolute leak rate of the reference tube, although negligible, is unknown. Using a capillary tube (CT), connected with any tube, it is possible to eliminate this quantity. The idea of this method is based on the fact that we can predict the leak rate of the CT using appropriate theoretical models in comparison with our experimental results. Therefore, the on-line auto-calibration of our system is possible using this technique. For more details see ref. [5].

Gas leak tests using two CT's with inner radius 5 μm and lengths 350 and 111 mm respectively, have been performed by connecting them alone and in combination (in series) to achieve absolute measurements. The total length of 461 mm was found to give a leak rate close to the nominal one, that is $(1.063\pm0.020)\times10^{-8}$ bar×l/s). The prediction using a theoretical model was 1.025×10^{-8} bar l/s, assuming we know the radius of the CT to be 5 μm. Therefore, the two values are consistent within ±3.6%.

The radius of the CT might be known from the manufacturer, but we tried to determine it experimentally. Thus, we used the image obtained by an optical microscope and compared with that of an optical grating having 300 lines/mm (3.33 μm per line). The diameter of the CT corresponds to 3 lines of the grating ($\approx$10 μm) with an uncertainty of the order of ±2 μm.

Some experimental results

The evaluation of the described system has been performed testing a certain number of tubes with various leak rates. From the obtained results, we arrived at various conclusions concerning the variations over a number of tubes (usually the 25 tubes of each layer) and the degree of repeatability as well.

The obtained standard deviation for the gas leak rate, on the average, was found to be $\sigma_t \approx 0.08\times10^{-8}$ bar×l/s during a lot of tests (0.08 of the accepted leak rate). This value includes the statistical fluctuations of the test and statistical fluctuations due to the production as well.

Furthermore, we studied the consistency of the tests by performing two successive measurements for the same tubes in a time interval of 3 days. The obtained linear correlation coefficient found to be ρ=0.85, leading to the conclusion that the statistical uncertainties are sufficiently small, although the range of the leak rate along the particular tubes was very narrow.

For the gas leak measurement 2 people are needed. It takes 1.5 h to put the tubes in each box and 1.5 h to take them out from each box. The measurement takes 30 min per box.

Figure 15 shows typical results.

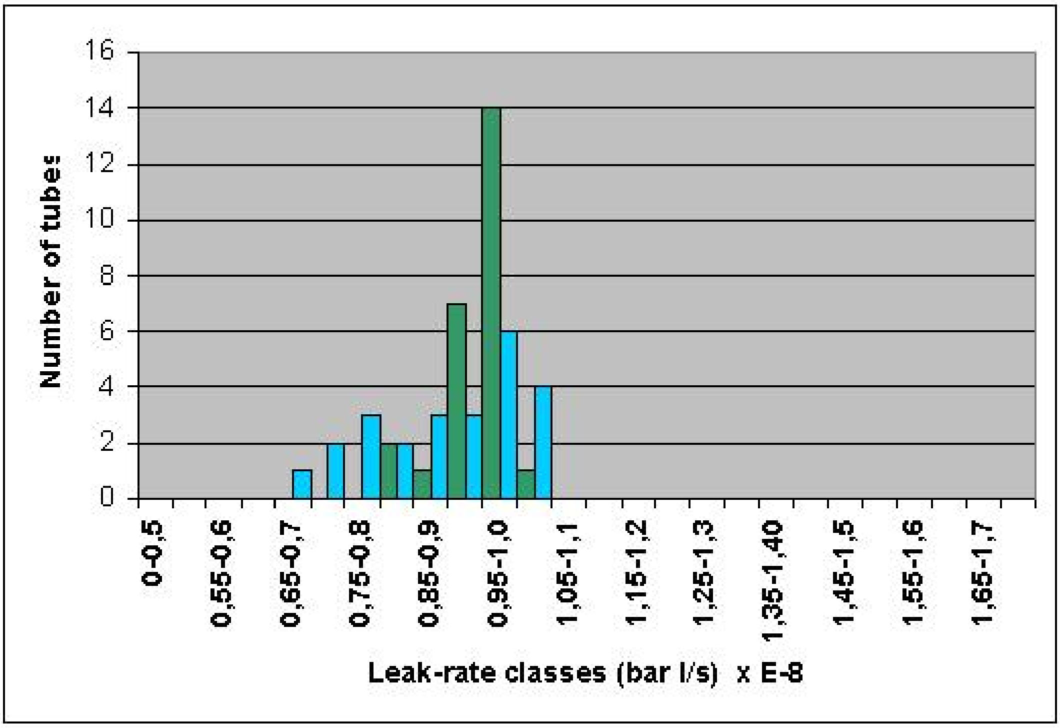


Figure 15: Typical gas leak rate. The green (darker) bars show the distribution of the lower layer tubes while with the blue (lighter) ones show the distribution of the upper layer.

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References

[1] ATLAS Muon TDR 10, CERN/LHCC/97-22, 31 May 1997

[2]. CAEN SY 502 User's Manual

[3]. An electromagnetic micrometer to measure wire location inside an ATLAS MDT drift tube, M. Cambiaghi et al., NOTE-ATLAS-MUON-98-259, 12 Nov 1998

[4]. Differential Manometer for gas leak measuring. http://atlas.web.cern.ch/Atlas/project/MDT/www/mirrordubna/atlas/QAQC/chleak/dfmanom.htm, G. Chelkov et al

[5] S. Maltezos, M. Dris, E. N. Gazis, "Calibration of the Gas Leak using Capillary Tubes", under preparation .

Appendix I

Temperature dependence of wire tension

Let a material object that has an initial length L_0 at some temperature θ_0, its length changes to L when the temperature becomes θ. We have:

$$L - L_0 = L_0(\theta - \theta_0)\alpha$$

a is the average temperature coefficient of linear expansion for the material in K^{-1}.

According to Hooke's law a material, that might be already under stress, can be streched from L_0 to $L=L_0+\Delta L$ by applying on it additional tensile stress, we have

$$\frac{F}{S} = Y\frac{\Delta L}{L_0}$$

where: $\frac{\Delta L}{L_0}$ is the tensile strain, Y is the Young's modulus, F is the additional force and S is the cross sectional area of the material. We assume that all quantities are positive and we take care of the fact that the length could increase or decrease depending on the direction of the force. Let us assume that at temperature θ_0 both the aluminum tube and the wire are at some tension and have the same length L_0, see Fig. I1.

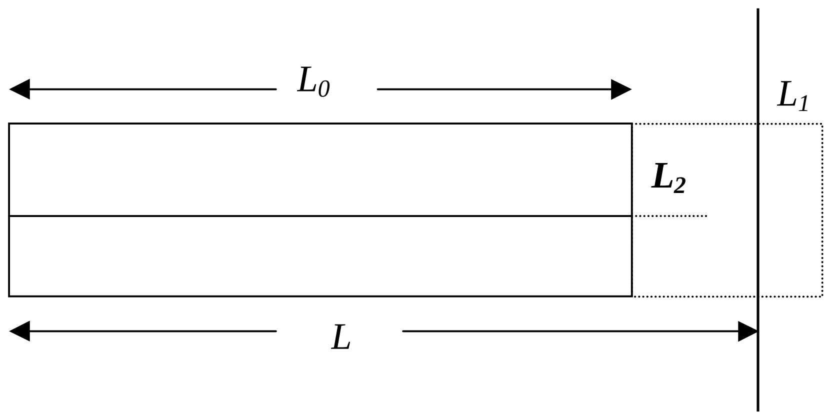

Figure I1: Diagram for calculating the forces due to temperature change on the wire and tube body.

If the temperature increases and becomes θ, and we imagine that the mechanical tension for both aluminum and wire remain as before then the lengths of the two materials would be different L_1 and L_2 respectively. In this case the aluminum will become longer (if the temperature decreases the opposite will be true).

$$L_1 - L_0 = L_0(\theta - \theta_0)a_{Al} \qquad \text{and} \quad L_2 - L_0 = L_0(\theta - \theta_0)a_W$$

According to a known principle, if the two materials are forced to get a length L at temperature θ, then an additional force F is needed such that

$$L_1 - L = L_1 \frac{1}{Y_{Al}} \frac{F}{S_{Al}}$$

$$L - L_2 = L_2 \frac{1}{Y_W} \frac{F}{S_W}$$

where L is the final length for both aluminium tube and wire. For a temperature increase $L_2 < L < L_1$ because $\alpha_{Al} > \alpha_W$.

From the above relations we get,

$$L_1 - L_2 = L_0(\theta - \theta_0)(\alpha_{Al} - \alpha_W)$$

$$L_1 - L_2 = F\left(\frac{L_1}{Y_{Al}S_{Al}} + \frac{L_2}{Y_W S_W}\right)$$

$$F = \frac{L_1 - L_2}{\dfrac{L_1}{Y_{Al}S_{Al}} + \dfrac{L_2}{Y_W S_W}}$$

Finally,

$$F = \frac{Y_{Al}S_{Al}Y_W S_W (\alpha_{Al} - \alpha_W)\Delta\theta}{Y_W S_W (1 + \alpha_{Al}\Delta\theta) + Y_{Al}S_{Al}(1 + \alpha_W \Delta\theta)}$$

Taking into account that

$$1 >> \alpha_{Al}\Delta\theta \quad \text{and} \quad 1 >> \alpha_W \Delta\theta$$

we have the approximate formula

$$F \approx \frac{Y_{Al}S_{Al}Y_W S_W (\alpha_{Al} - \alpha_W)\Delta\theta}{Y_W S_W + Y_{Al}S_{Al}}$$

$$\frac{F}{\Delta\theta} \approx \frac{(\alpha_{Al} - \alpha_W)}{\dfrac{1}{Y_{Al}S_{Al}} + \dfrac{1}{Y_W S_W}}$$

We use the values of the various quantities,

$$\alpha_{Al} = 24 \times 10^{-6} \text{ /K}$$

$$\alpha_W = 4.4\times10^{-6}\ /\text{K}$$

$$Y_{Al} = 7\times10^{10}\ \text{N/m}^2$$

$$Y_W = 40\times10^{10}\ \text{N/m}^2$$

We take into account that the diameter of the wire is d=(50±0.5) μm, the external diameter of the tube is D=($30\pm^{0.000}_{0.030}$) mm and the wall thickness is (400±20) μm, and we find,

$$\frac{F}{\Delta\theta} \approx 1.5\ \text{gf/K}$$

This has been confirmed experimentally.

Appendix II

Gas Leak Calculations

The idea behind the gas leak rate definitions and measurements is as follows. For ideal gas we have the known formula,

$$n = (\frac{1}{RT} pV)$$

Assuming that T and V are constant, the leak as quantity of substance per unit time (in mol/s) is given by,

$$\frac{\Delta n}{t} = \frac{V}{RT} \frac{\Delta p}{t}$$

Assuming that T is the room temperature (approximately 295 ^{0}C), for a measurement of the leakage, one could refer to the quantity

$$L = RT \frac{\Delta n}{t} = V \frac{\Delta p}{t}$$

Let us see in detail the differential manometer method. See Figure II1.

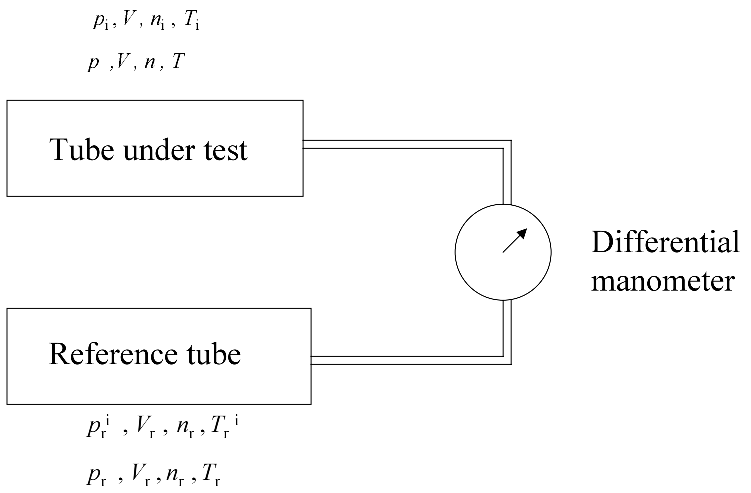

Figure II1: Tube under test and reference tube at initial and final conditions.

Index i stands for initial values (when the first measurement is taken) and r for the reference volume. We have for the volume of the tube under test and the reference volume respectively the relations,

$$n^i = \frac{p^i V}{RT^i} \quad \text{and} \quad n = \frac{pV}{RT}$$

The leak rate is $$\frac{n^i - n}{t} = \frac{V}{tR}\left(\frac{p^i}{T^i} - \frac{p}{T}\right)$$

We use instead the quantity $L = RT\frac{n^i - n}{t} = \frac{V}{t}\left(\frac{T}{T^i}p^i - p\right) = \frac{V\Delta p'}{t}$, where $\Delta p'$ is the pressure difference reduced to the final temperature of the tube under test.

Let $\Delta p = p_r - p$ be the final pressure difference of the reference volume and the tube in their final temperatures T_r and T respectively. The way we perform the measurements corresponds to $p^i = p_r^i$. We have

$$\frac{p_r^i V_r}{T_r^i} = \frac{p_r V_r}{T_r} = \frac{p^i V_r}{T_r^i} \quad \text{or} \quad \frac{p_r}{T_r} = \frac{p^i}{T_r^i}$$

$$\text{so} \quad L = \frac{V}{t}\left(\frac{TT_r^i}{T^i T_r}p_r - p\right)$$

We define $F_T = 1 - \frac{TT_r^i}{T^i T_r}$ and finally we get $L = \frac{V}{t}(\Delta p - F_T\, p_r)$

We call F_T Temperature Influence Factor (TIF). If $F_T = 1$ then the pressure difference even though, in general, measured at different final temperatures is the correct pressure drop to be used. If this is not the case the pressure drop Δp has to be corrected by adding the term $-F_T\, p_r$. We observed temperature differences $T - T_r = \pm 0.05$ K and $T^i - T_r^i = \pm 0.05$ K. This leads to a correction, $-F_T\, p_r = 0.7$ mbar .