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The Freiburg MDT leak test setup

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Abstract

The Atlas QA/QC procedure requires every MDT to be checked individually for gas tightness after its production. An apparatus was designed to measure the MDT leak rate by means of detecting the leaked gas in a surrounding vacuum using a mass spectrometer. A gas mixture of Ar-CO_2 93:7 is used, allowing the leak test to be performed at the same time as the high voltage stability test. This note describes the Freiburg prototype system as well as systematic studies with the setup.

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1 Introduction

Of the approximately 380 000 Atlas Monitored Drift Tubes (MDTs) roughly 10 000 will be built in Freiburg during the next few years. To ensure a correct performance of the Atlas muon spectrometer the MDT community agreed among others on a strict set of specifications to be verified for every individual tube [1]. One of the requirements is that of gas tightness, which is defined as a leak rate Q_l below the maximum acceptable rate of

$$Q_{l,max.} = 1 \cdot 10^{-8}\,\mathrm{bar} \cdot \mathrm{l/s}. \tag{1}$$

Equation 1 holds for the standard MDT gas mixture Ar:CO_2=93:7 at an absolute pressure of 3 bar inside and 1 bar on the outside of the tubes.
A standard industrial procedure to test parts for gas tightness is to fill them with some easily identifiable tracer gas and monitor its concentration in the neighbourhood of the parts investigated. An increase in the tracer gas concentration then corresponds to a leak in the object being tested. The most common tracer gas is helium, with the advantage of a very low natural concentration in the atmosphere and thus a high sensitivity of the method even to leaks as small as 10^{-11}mbar$\cdot$ l/s [2].
The leak rate Q_l of a given system depends on the viscosity η and the molecular weight of the used gas. The exact relationship is further dependent on the flow regimen (viscous laminar, viscous turbulent or molecular) of the leak [3], which is normally unknown. To avoid the difficulties and uncertainties arising from converting helium leak rates to the ones relevant for the Atlas MDTs (i.e. Q_l for Ar:CO_2) it was decided by our group in Freiburg to use the standard Ar:CO_2 mixture instead of helium as a tracer gas. Further reasons for this decision were the familiar problem of helium diffusion through the noryl endplug material [4] as well as the possibility to integrate the leak test into the also required high voltage stability test when using the standard MDT gas mixture.
For the test the MDTs are inserted into individual steel cylinders which are evacuated. A quadrupole mass spectrometer connected to the cylinders and tuned to mass 40 is used to measure the Ar concentration around the tubes.

2 Apparatus

The general scheme of the leak detection setup is shown in figure 1 for the prototype system capable of testing two MDTs in parallel. Every MDT is contained in a cylindrical steel case with an inner diameter of 40 mm. Special closing heads are used to seal the cylinder ends and to provide a gas connection to the MDTs (fig. 3). A reference leak with known Q_l used for calibration purposes is mounted in a third cylinder. The cylinders are connected to a central vacuum manifold via pneumatically operated valves (V1-1 to V1-3). The vacuum manifold is both connected to a pump system used to evacuate the cylinders around the MDTs and to the quadrupole mass spectrometer Satellite 200 D (manufacturer Leda-Mass Ltd.,

Crewe, UK). The pump system can also be used to evacuate the interior of the MDTs prior to filling them with the Ar:CO_2 mixture by opening valve V4. In order not to possibly contaminate the MDTs with oil residues a dry pump system was chosen consisting of the scroll pump ESDP 12 and the turbo molecular pump EXT 351 E (manufacturer Edwards BOC, Crawley, UK). Several pressure gauges PG are used to monitor the vacuum and the pressure within the MDTs.
The mass spectrometer is controlled by RS 232 from a PC. This can either be done using the software RGA for Windows supplied with the instrument or with a programme specifically developed for this purpose on a linux PC. The pressure controllers yield analog output signals related to the pressure present in the system, which are read out via a computer controlled multimeter HP 34970 A (manufacturer Hewlett Packard Co., US) and a GPIB connection. The electropneumatic valves can be opened and closed from the PC with the help of a digital I/O board (CIO-DIO 192, Computer-Boards Inc., Middleboro, US) and a group of relays. All components of the setup were chosen in such a way as to allow the system to be operated in a mostly automated way consistent with mass production.

Test procedure

For the leak test the MDTs to be examined are inserted into the steel tube cases and connected to the gas supply using the closing heads. The interior of the MDTs and the vacuum system (steel cylinders and manifold) are evacuated using the fore pump P2 (valve V4 open, gas supply V5 closed) until the pressure within the MDTs is below 1 mbar, as required by [1]. When this point is reached, V4 is closed and the evacuation of the tube cases is continued with the turbo pump T2 until the pressure is sufficiently low for the leak measurements. This step takes on average about 30 to 45 minutes.
For a measurement of the natural argon background in the vacuum system the tube cases are successively connected to the mass spectrometer and the argon partial pressure is recorded. The calibration leak is connected to the gas supply by opening V5 (H2 closed) and the resulting argon partial pressure in the system is measured as a reference.
After the background measurements are finished the MDTs are filled with the test gas (open H2), while the mass spectrometer is disconnected from the system (V2 closed). The pressure inside the MDTs is monitored as well as the quality of the vacuum surrounding the drift tubes. A significant worsening of the vacuum conditions (increasing pressure) allows one to detect large leaks without the danger of damaging the spectrometer during the actual measurement, as would be the case when operating the Satellite 200 D at too high pressures. If this is the case, the corresponding tube is excluded from the further test procedure. After a gas pressure of 3 bar (abs.) is reached inside the MDTs, each tube is in turn connected to the mass spectrometer using the valves V1. The argon concentration is recorded as well as the partial pressure caused by the reference leak alone. The measurement time for each MDT is about 3 minutes.

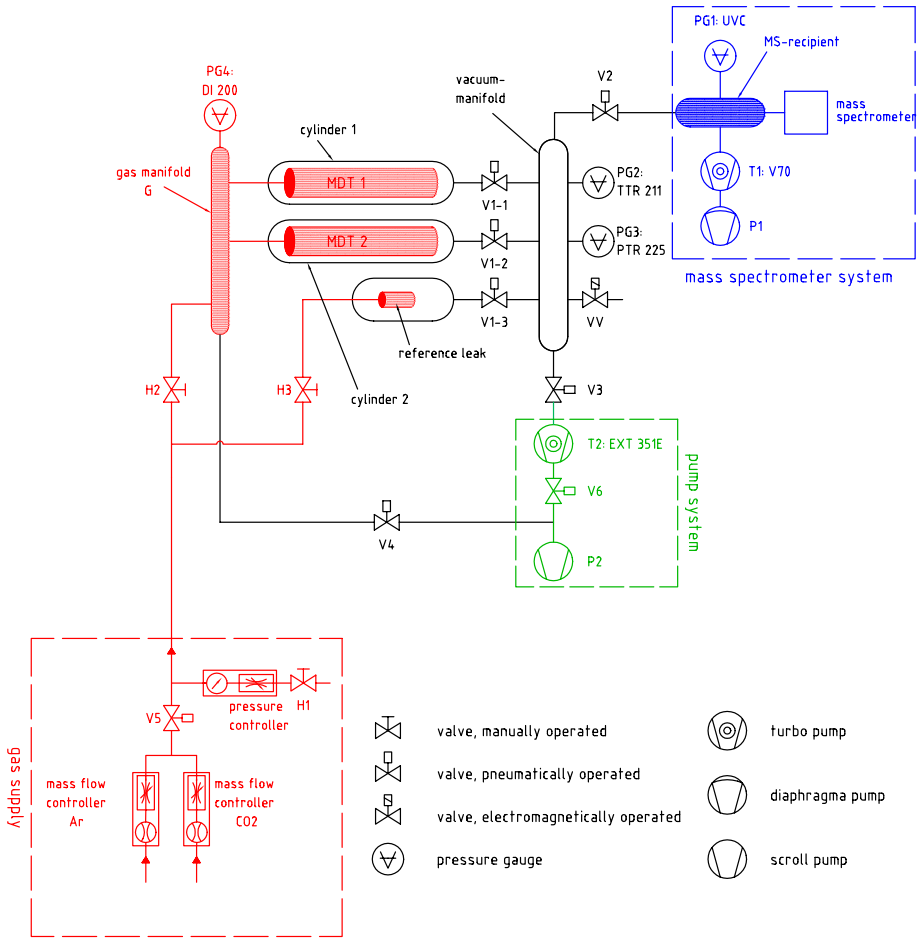

Figure 1: General scheme of the Freiburg leak detection system (prototype)

Figure 2: The prototype system. The left photograph shows the complete setup, the right photograph the end of one of the cylindrical vacuum tanks with an inserted MDT.

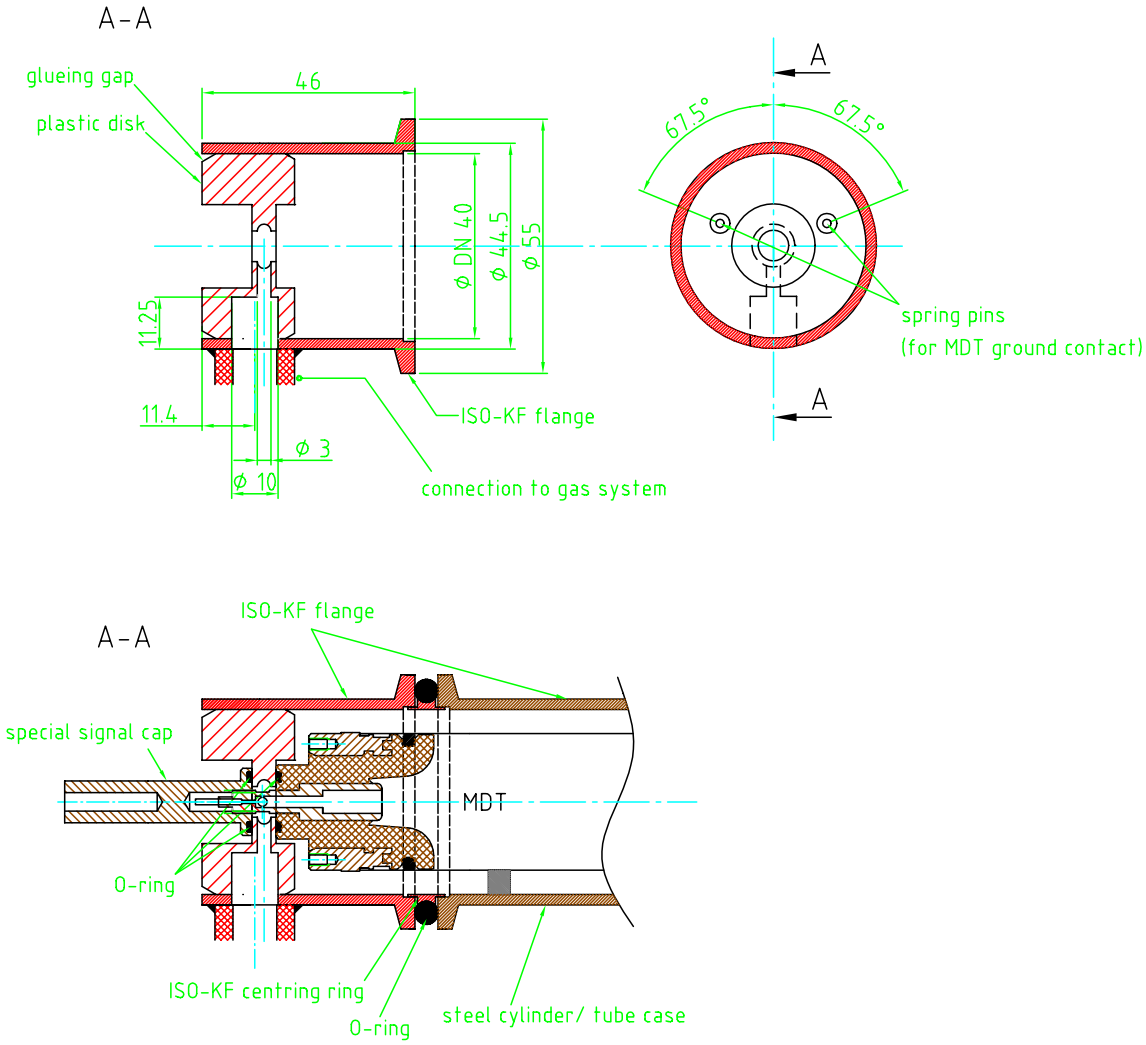

Figure 3: One of the closing heads used to seal the cylindrical steel cases and to provide the gas connection to the MDTs. The upper part of the drawing shows the technical details, the lower part the ensemble of MDT, steel cylinder and closing head. Every closing head consists of a stainless steel ISO-KF bellows flange with an insulating plastic insert. An off-axis bore is used to connect the MDTs to the external gas supply. The connection between MDT and closing head is made gas tight by using two standard O-rings and screwing on of the signal cap. The vacuum volume inside the steel cylinders is sealed by using a centring ring between the ISO-KF flanges at the end of the tube case and the closing head.

Calculation of MDT leak rates

The leak rate $Q_l(i)$ of the i-th MDT is

$$Q_l(i) = \left(\frac{p(i) - p_{back.}(i)}{p_{ref.}(i)} \right) \cdot Q_{l,ref.}\,, \tag{2}$$

where $p(i)$ is the recorded argon partial pressure when tube i is connected to the mass spectrometer, $p_{back.}(i)$ the corresponding background and $p_{ref.}$ the argon pressure caused by the reference leak. $Q_{l,ref.}$ is the leak rate of the reference leak.
The $Q_l(i)$ calculated in equation 2 are the leak rates assuming a pressure of 0 bar (vacuum) in the neighbourhood of the MDTs. To compare the obtained values to the maximum acceptable rate of equation 1, which is specified for atmospheric pressure on the MDT outside, a correction needs to be applied. As already mentioned in the introduction for the case of different gases, converting leak rates measured at certain conditions such as pressure, temperature, etc. to different conditions is complicated since the necessary relations depend on the prevailing flow regimen.
For the two main cases, viscous-laminar and molecular flow, the pressure dependence is given by

$$\frac{Q_l(p_{a1}, p_{b1})}{Q_l(p_{a2}, p_{b2})} = \begin{cases} \dfrac{p_{b1}^2 - p_{a1}^2}{p_{b2}^2 - p_{a2}^2} & \text{(viscous-laminar flow)} \quad (3a) \\ \dfrac{p_{b1} - p_{a1}}{p_{b2} - p_{a2}} & \text{(molecular flow),} \quad (3b) \end{cases}$$

where p_{b1}, p_{b2} are the pressures on the high pressure side , p_{a1}, p_{a2} the pressures on the low pressure side of the leak [5].
If one applies equation 3 to the case of the Atlas MDTs, one gets for the leak rates at standard Atlas operating conditions

$$Q_{l,corr.} = \frac{8}{9} \cdot Q_l \quad \text{for viscous-laminar flow} \tag{4}$$

$$Q_{l,corr.} = \frac{2}{3} \cdot Q_l \quad \text{for molecular flow,} \tag{5}$$

where Q_l is the rate from equation 2.
Relation 5 is used by our group for the conversion. This seems to be justified for two reasons: Firstly, using equation 5 one is 'on the safe side', meaning that any MDT which meets the Atlas specification under the assumption of laminar flow will also meet the specification assuming a molecular flow behaviour. Secondly, it is reasonable to consider the flow through any leak as laminar on the high pressure side with a possible transition to molecular flow over the length of the leak channel. One can then show that the overall pressure dependence of Q_l is dominated by the laminar part.

3 Calibration

In order to calculate the MDT leak rates according to equation 2 the rate $Q_{l,ref.}$ must be known. In Freiburg a so called standard leak type 10014, bought from Ai Qualitek Limited, Cambridge, UK, is used as reference for the measurements. The leak is made of a porous ceramic material, which was compressed with the help of a metal casing until a defined gas permeability was reached. The design leak rate is $1 \cdot 10^{-7}$ bar $\cdot$ l/s for argon at 3 bar absolute pressure and 1 bar in the neighbourhood of the leak.
The reference leak was recalibrated here in Freiburg measuring the pressure increase in a small vacuum volume with time. This gave us the actual leak rate for 0 bar on the low pressure side of the leak, as is the case in the MDT leak test described in the previous section. We also repeated the calibration procedure for different gas pressures, thus being able to create different leak rates. The result of the calibration measurements is shown in figure 4. The data points can be parametrised by a second degree polynomial. This is plausible from equation 3, if one assumes a mixture of molecular flow behaviour/ diffusion (porous ceramic material) and a few larger leak channels (laminar flow).

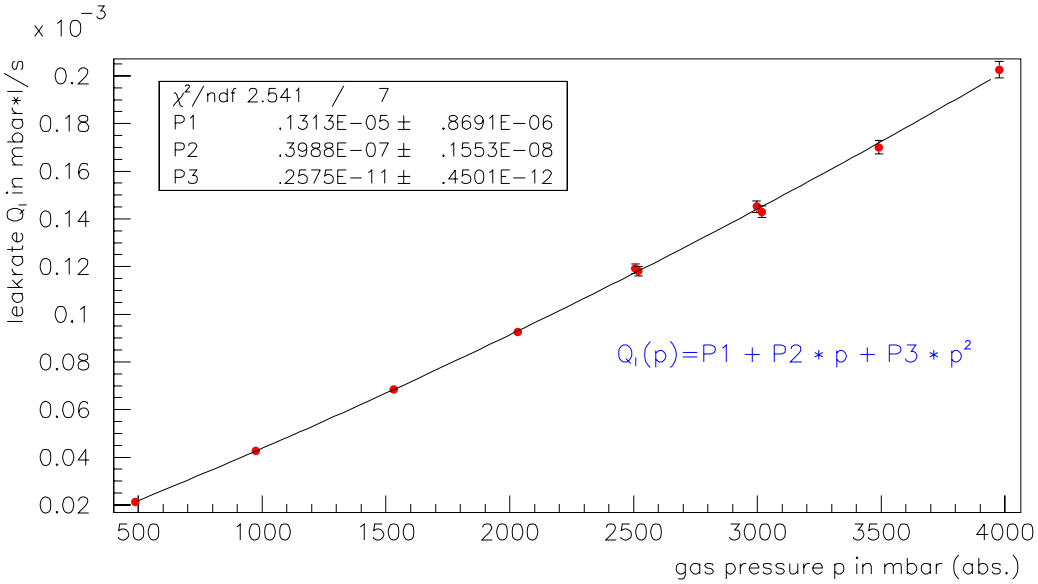

Figure 4: The rate Q_l of the Freiburg reference leak versus the applied gas pressure p. The plot also shows the results of a quadratic fit to the data points.

4 Measurements and systematic studies

Linearity

The calibration curve from figure 4 was used to check the linearity of the mass spectrometer response by applying different gas pressures to the reference leak and recording the argon partial pressure in the system. The results of these measurements are shown in figure 5. Two different filaments of the mass spectrometer were used. One can see that the argon partial pressure seen by the spectrometer is indeed proportional to the leak rate and thus equation 2 can be used.

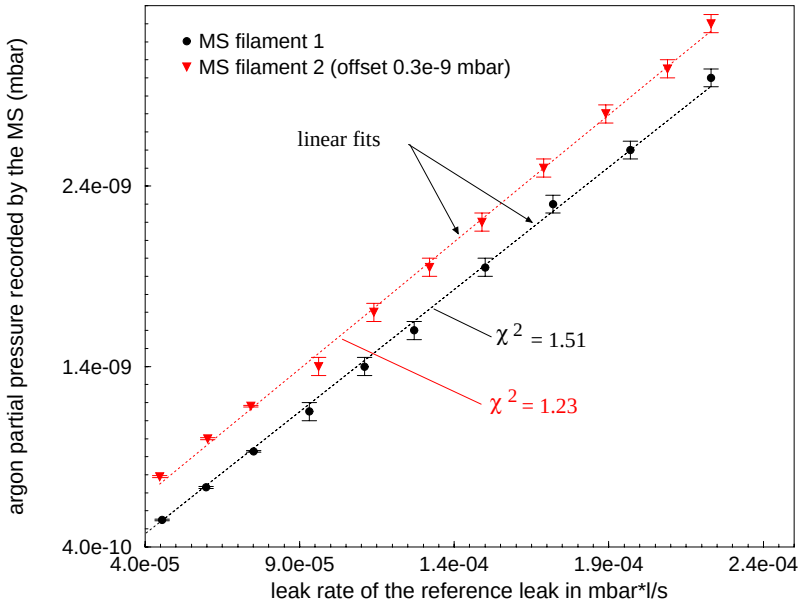

Figure 5: Linearity of the mass spectrometer response to different argon concentrations.

Measurement uncertainties

The accuracy of the obtained MDT leak rates Q_l depends on the uncertainty of the quantities in equation 2. It is reasonable to distinguish between errors in the recorded argon partial pressures and any uncertainty of the reference leak rate $Q_{l,ref.}$. Since only the ratio of partial pressure readings is relevant to equation 2, the absolute calibration of the mass spectrometer, i.e. the relation between the actual argon concentration at the spectrometer entrance and the produced signal, is of no importance. On the other hand it is critical that the signal corresponding to a given argon concentration (leak rate) is the same when measuring $p_{ref.}$ and p, $p_{back.}$. To see whether this is true the mass spectrometer signal was recorded over several hours for a constant leak rate (reference leak with fixed gas pressure).
The results of two such measurements are shown in figure 6. The rapid signal

increase in the beginning is caused by the warming up of the mass spectrometer filaments and an increasing electron emission leading to a larger number of gas ionisation processes per time. It can be clearly seen from this behaviour that the mass spectrometer should be switched on 30 to 60 minutes before the first measurement. After the initial increase the signal still shows some slow variations of the order of 10 to 20 % over several hours. A negative effect of these variations on the accuracy of the measured MDT leak rates can be avoided, if the argon partial pressure $p_{ref.}$ caused by the reference leak is checked with every (few) MDT measurement(s), as is the case in the test sequence chosen in Freiburg.
It should also be noted that the mass spectrometer signal for a given argon (or any other gas) concentration decreases slowly with time independent of the variations described above. This effect stems from ageing processes of the filaments with the consequence of a reduced electron emission and resulting gas ionisation.
If the effect of slow signal variations can be neglected (e.g. by frequently taking a reading of $p_{ref.}$ as described above) the uncertainty of the p and $p_{ref.}$ can be estimated by the scattering of several data points. For $p_{back.}$ it needs also to be taken into account that the background in the system is largely caused by argon molecules released from the walls of the vacuum vessels. This effect is known as desorption and decreases with time. Since the background measurements are done significantly earlier than the MDT measurements (time needed for filling the MDTs, ...), the background will most certainly be lower at the time of the MDT leak rate determination (measurement of p) thus yielding a too small value of Q_l.
The effect of a varying desorption can be neglected if the background level is much smaller than the argon concentration caused by a leak in one of the MDTs. We

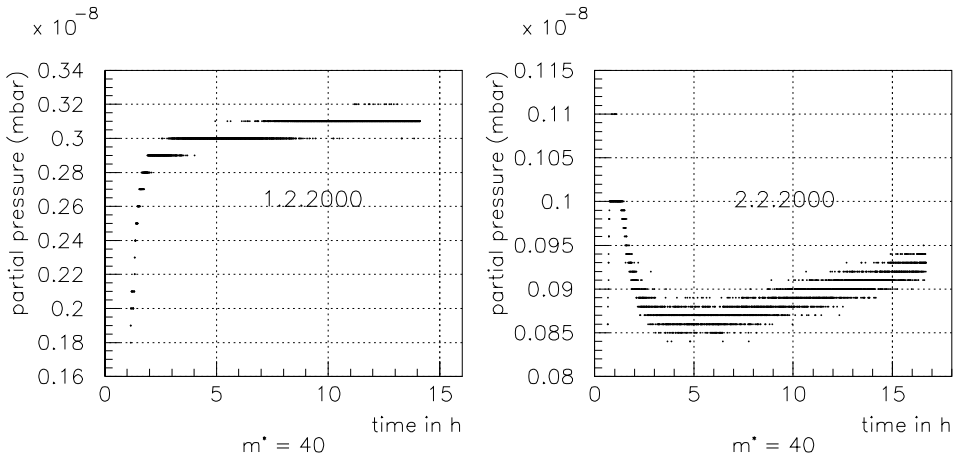

Figure 6: Stability of the mass spectrometer output for a given leak rate argon concentration. The rapid increase in the signal over the first 45 minutes is a typical filament warming up feature. The different absolute values of the recorded partial pressures in the two presented data sets are due to using spectrometer filaments of 'different age'. (right plot: filament more heavily used, resulting in a lower signal)

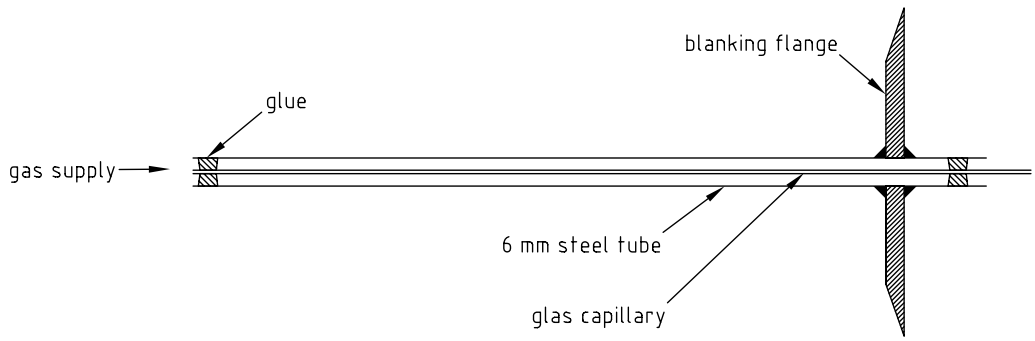

Figure 7: Schematic drawing of one of the capillary leaks

found that with our setup a pump down time prior to the measurements of about 45 minutes is sufficient to get a statistical error of 5 to 10 % for a Q_l of the order of the Atlas specification.
The largest error in equation 2 is the uncertainty of the reference rate $Q_{l,ref.}$. As described in section 3 the standard leak 10014 was calibrated using the pressure increase method. The accuracy of the obtained leak rate $Q_{l,ref.}$ is limited by the precision of the pressure sensor (Thermovac Transmitter TTR 211 S, manufacturer Leybold Vacuum GmbH, Cologne). In addition to the intrinsic measurement uncertainty the result had to be multiplied by a conversion factor only roughly known to take into account that the sensor output was calibrated for air instead of argon. The overall precision of $Q_{l,ref.}$ is then approximately 20 %, the uncertainty of the calculated MDT leak rates Q_l approximately 25 %.

Reproducibility

To check the reproducibility of the measurements 'artificial' leaks were built, connected to the gas supply and used instead of MDTs. In this we followed an idea developed by the Rome 1 group using glass capillaries with an inner diameter of 5 to 10 μm. The capillaries were glued into a 6 mm steel tube which allowed a connection to the gas system to be made at one end. The other end was welded to a vacuum ISO-KF blanking flange which in turn was used instead of one of the usual closing heads (fig. 7). Dependent on the capillary length different leak rates of the order of the Atlas specification can be realised.
Figure 8 shows the result of a repeated determination of Q_l for two of the capillary leaks as well as for one of the MDTs. The obtained Q_l's are within their uncertainties consistent with a constant value for every leak, as expected.

5 Outlook

The next step after completing and extensively testing the prototype system is to finish the design and installation of a larger system to be used in the tube mass production from next year on. The foreseen setup can test up to 20 MDTs in one go. Further work also needs to be done in automating the test procedure and in

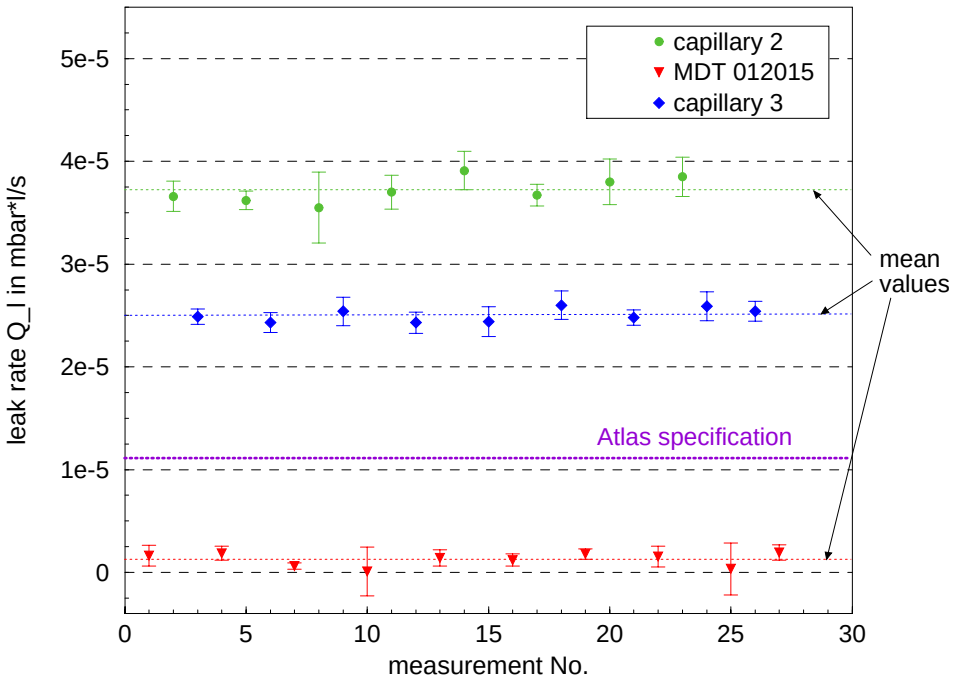

Figure 8: Reproducibility of the leak rate measurement. Instead of applying relation 5 to the calculated leak rates the maximum acceptable rate according to the Atlas specifications was adjusted for a surrounding pressure of 0 bar.

combining the leak test with the high voltage test.

6 Conclusions

A prototype test system to check the MDTs for gas tightness has been developed for the MDT production in Freiburg. The basic principle of operation is the detection of argon emanated from the gas filled drift tubes into a surrounding vacuum vessel with the help of a quadrupole mass spectrometer. All components of the apparatus were chosen in such a way that they can be controlled remotely from a PC thus allowing automatisation of the test procedure.
Various systematic studies have been carried out proving the functionality of the system and showing that the statistical uncertainty of the obtained MDT leak rates is 5 to 10 %, with an additional systematic error of roughly 20 % due to the limited precision of the reference leak calibration.

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