First experience with the prototype Atlas MDT gas circulation system at GIF

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Abstract

In addition to being the largest detector subsystem in size, the MDT part of the Atlas Muon Spectrometer also comprises a significant active gas volume of roughly 800 cubic meters. Although the chosen MDT operating gas, Argon:CO_2 in relation 93:7, is made up of fairly inexpensive and inert standard gases, financial and technical constraints still necessitate that the detector gas is circulated through the Atlas MDT system with only a small percentage being replaced each cycle.
A first test system, using the final Atlas MDT gas circulator, has been built and is at present under study at the CERN Gamma Irradiation Facility GIF together with a BIS type MDT chamber. This note describes the test setup, the goals of the measurement program and summarises first experiences with the system.

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total volume:	754 m^2
operating pressure:	3.0 bar abs.
gas composition:	Ar (93 ± 0.25 %)
	CO_2 (7 ± 0.25 %)
number of chambers:	682 (barrel) + 512 (end cap)
number of gas channels:	112 (barrel) + 162 (end cap)
gas circulation:	1 volume/day
refreshing rate:	10% of total volume/day
base line impurities:	≤ 100 ppm O_2
water content[3]	500 - 1000 ppm

Table 1: Atlas MDT gas system specification [1]

1 The Atlas MDT gas system

The MDT part of the Atlas Muon Spectrometer is made of approximately 380 000 pressurised drift tubes, which are grouped into 1200 chambers of different size. After extensive studies covering both performance and ageing aspects, a mixture of Ar:CO_2 in the ratio 93:7 %-Vol at 3 bar (abs.) was finally chosen as the operating gas. Attempts to use a more linear drift gas like e.g. Ar:N_2:CH_4 = 91:4:5 were given up since these gases pose a too great risk in terms of detector ageing for the planned 10 year operation period of LHC. Numerous ageing studies (e.g. [2],[3]) carried out in that context also clearly showed the importance of uncontaminated, oil- and lubricant free gas system components. Table 1 summarises some of the remaining requirements of the MDT gas system.

Gas circulation

As mentioned above, mainly financial reasons forbid an operation of the full Atlas MDT system in vented, one-pass mode. A daily gas refreshing rate of 10% [4] of the total detector volume per day has been chosen as the baseline. The gas circulation rate in the MDT detector will be higher by a factor 10, i.e. 1 volume/day, based on the concept that any contamination, whether by irradiation effects on the gas in the inner regions of the muon system, or by any leaks in the system, is thus diluted and its impact on the detector performance reduced. Finally appropriate filtering for water, oxygen or any other relevant contaminants can be applied to part of the circulating gas in order to further stabilize gas quality and integrity if required.

2 The circulatory test system at GIF

The prototype system built for testing and evaluation at the CERN Gamma Irradiation facility GIF uses the final Atlas gas circulator, a custom-designed high speed compressor type ATC manufactured by the Czech company Ateko [5], together with a specially designed

[3] Sustainable water concentrations are limited to a maximum of 1000 ppm in order to exclude corrosion of the compressor blades

[4] with some recent discussion of a further reduction to 5%

[5] Aparáty Technologie Konstrukce, Hradec Králové, Czech Republic

Nominal operating gas flow	100 Nm^3/h
Maximal flow rate	200 Nm^3/h
Gas pressure at inlet	$\approx$2.9 bar
Gas pressure at outlet	$\approx$3.2 bar
Maximal power at full speed	2.5 kW
Maximal speed	55 000 rpm
Electrical Supply	3× 380 V 3 phase, up to 4.54 A each

Table 2: Operation parameters of the gas circulator ATC [4]

gas system setup which allows simulation of the later Atlas operation. A BIS type final Atlas MDT chamber (module zero) was chosen as detector volume, which allows not only a test of the functionality and stability in terms of operation of the gas system, but also a study of the chamber behaviour under the combination of a high irradiation rate, delivered by the GIF installation, and a circulating gas.

The ATC gas circulator

In the final Atlas detector, the purpose of the gas circulator is to compensate for the occurred pressure drop in the gas returning from the previous pass through the detector by compression. An overall pressure drop of 300 mbar in the cycle is envisaged for the system. The two main restrictions in the choice of a suitable apparatus are the high flow rate of 100 Nm^3/h and the requirement of a completely oil- and lubricant free design in order to avoid any risk of ageing critical contamination of the MDT operating gas.
The chosen **Argon Turbo Circulator**, ATC, comprises a high speed gas turbine running at up to 55 000 rpm. The concept of gas bearings, where the rotating turbocompressor wheel 'floats' on a cushion of the pumped gas itself eliminates the need for lubrication. The main characteristics of the ATC are summarised in table 2. Figure 1 shows the compressor after installation in the MDT test setup at GIF. One of the difficulties in building an appropriate down-scaled test setup lies in the only within tight limits adjustable ATC gas flow with a naturally much smaller system than the full Atlas MDT detector. In the system described this problem was solved by incorporating a large bypass loop into the gas circulation, thus allowing the nominal Atlas flow of 100 Nm^3/h to be pumped by the compressor, while in fact only a small fraction of less than 0.1% was sent through the BIS MDT chamber under study.

The MDT BIS test chamber

Given the very limited space at the GIF installation, a 8 layer BIS module zero [5] as one of the smallest Atlas MDT chamber was chosen as a test detector for the present study, the module zero also combining the advantages of

a. being a final production design with final components and materials

b. being the BIS series module zero, which is only foreseen as a spare chamber for the final Atlas system, which reduces the negative consequences of any acquired ageing effect during the irradiation at GIF.

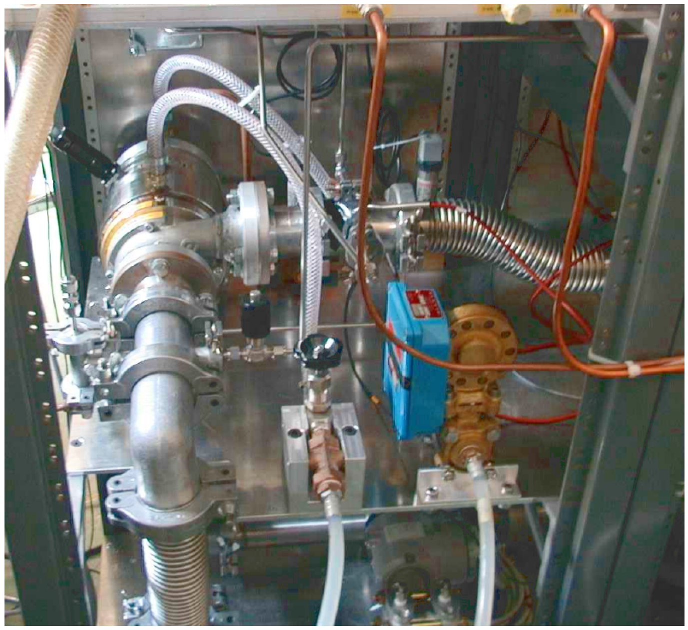


Figure 1: The ATC installed in the MDT test system at GIF

The chamber was equipped with the final MDT on-chamber gas system in full parallel mode, i.e. all tubes being supplied separately from 2×2 manifolds at the chamber ends. From the point of electronics the chamber is equipped with the standard (prototype) MDT front end boards and read out chain; measurements of drift times and track reconstruction are possible. For 80 of the 240 BIS tubes the pulse height (actually the pulse charge) can be measured in addition, which especially serves to detect any gain degradation.

Gas supply and regulation system

The full gas supply and regulation system is schematically shown in figure 2. Except for the analysis equipment, the system in principal consists of 2 independent subsystems, one for each multilayer of the BIS chamber under study. Though the main purpose of the MDT high rate test at GIF is the evaluation of the performance and any possible ageing effects under circulating gas conditions, half of the BIS MDTs (all tubes in multilayer 2) are operated in classical flushing mode. This is of particular advantage should any ageing or instability effects be observed in the system, since it will help to separate effects incurred by the gas circulation from any other phenomenons.
The used gas mixture, Ar:CO_2 93:7 is provided as a premix in batteries of $90\,\mathrm{Nm}^3$ in common for both the circulating chamber part and the one operated in flushing mode. The gas volume per battery is large enough to last for several months of operation.

Operation in flushing mode

Both BIS multilayers can be operated in flushing mode; the description of this non-standard mode for the normally circulated multilayer 1 is postponed to a later section. For multilayer 2 the basic necessary devices are a mass flow controller (MFC) (1)[6], type F-201C-RA-33-E, which allows to control the gas flow through the chamber, and a back

[6] labels correspond to figure 2

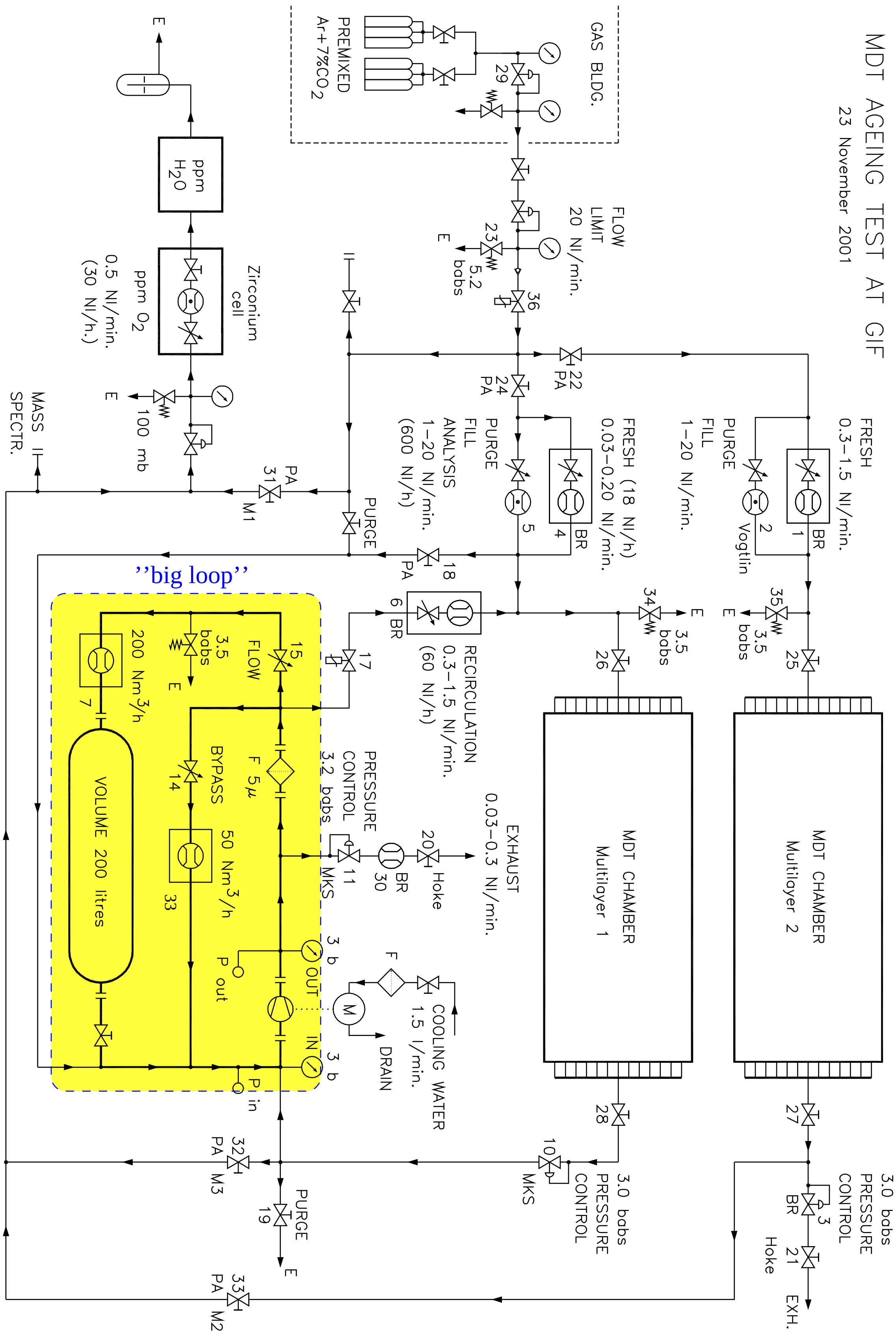


Figure 2: Schematic drawing of the MDT gas control and regulation system in use at the Gamma Irradiation Facility. The so called "big loop" of the circulating part of the system is highlighted.

pressure regulator (3), type P-702C-RA-33V to keep the drift tubes at the required pressure of 3 bar. Manufacturer for both devices is the Dutch company Bronkhorst[7]. Flow and pressure controller are electrically controlled by supplying an appropriate analogue input voltage as setpoint and by reading an output voltage corresponding to the momentary value. Since the adjustable flow rates through the MFC (1) are limited to a maximum of $\approx$ 100 Nl/h, an additional mechanical rotameter (2)[8] can be used in parallel to increase the gas flow, especially during filling and purging of the system. The pressure regulation has been found stable to 1 mbar with the absolute pressure calibration being accurate to about $\pm$10 mbar.

Operation in circulating mode

The circulating part of the prototype gas system consists of the so called "big loop", which acts as bypass for the major part of the circulating gas, and the "small" or chamber loop which supplies the BIS MDT chamber. With a nominal flow of 100 Nm^3/h operation lies within the turbulent flow regime. The need to limit cavitation and mechanical stress by vibration as well as the necessity to adjust the pressure drop in the loop to the rather small required range of the compressor (table 2) define the minimum mechanical dimensions in the bypass loop. While for the used stainless steel piping the actual pipe diameter is of less concern, the size of the used buffer volume is of importance; one would like to eliminate any additional gas volume as much as possible, since gas in this part of the system is not being exposed to irradiation as the MDT chamber itself and will thus lead to a dilution of any radiation-related ageing effects. After several tests in the lab a buffer volume of 200 liters was finally found as best suitable, realised as a roughly 1.50m long cylindrical container certified for use as pressure vessel at 3 bar. Two large diameter manual valves (14,15) allow the adjustment of the gas flow in the big loop. Additional elements are a particle filter (F) to retain dust and any material involuntary introduced into the system, 2 flow meters (7,33) for monitoring and two simple pressure gauges (12,13) to check the pressure before and after the compressor.
The drift tubes of multilayer 1 are supplied from the big loop via the mass flow controller (6)[9], while the fresh gas intake can be adjusted with mass flow controller (4)[10]. As for the multilayer 2 a second branch in parallel allows faster filling and/or purging of the system with larger quantities of fresh gas via MFC (5)[11].
As for the multilayer 2 flushing mode described above, the system is pressure driven, meaning that the exiting gas flow is regulated in such a way that the pressure in front of the pressure regulator is kept at a constant value. The main difficulty lies in the fact that the gas flow passing the back pressure regulator (10)[12] at the exit of the BIS chamber has to be "split", with a fraction corresponding to the fresh gas intake rate minus any possible leak rate being extracted from the system to exhaust while the rest is re-compressed and recycled. The somewhat naive concept to control the flow sent to exhaust also by a (mass) flow controller is difficult to implement since it requires that the relation

$$\dot{Q}_{out} = \dot{Q}_{in} - \dot{Q}_{leak}$$

[7] Bronkhorst HI-TEC, Ruurlo, NL
[8] Voegtlin Instruments AG, Aesch, CH, type V100-140.14, lubricant-free version for use with oxygen
[9] type F201C-FA-22V, Bronkhorst HI-TEC, Ruurlo, NL
[10] type as [9]
[11] type as [9]
[12] Baratron 690A with control valve 0248A-02000RV, MKS Instruments Inc., Andover, US

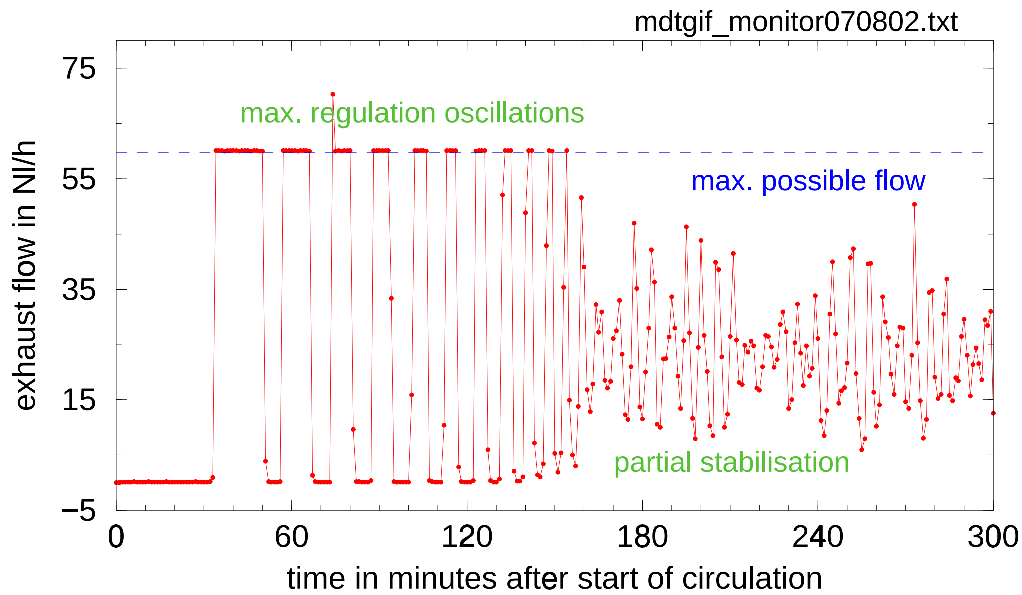


Figure 3: Monitored exhaust gas flow during 5 hours after the circulation was stopped for several hours and restarted. The fresh gas intake rate is 2 Nl/h.

is exactly met. This can not be realised by fixed setpoints on the flow rates but would necessitate some kind of feed back loop. For the prototype system at GIF a different approach was chosen, were the gas flow released from the system to exhaust is also pressure driven. The technical implementation is via the back pressure controller (11)[13] , set to approximately 3.2 bar (abs.), which was moved to the shown position on the high pressure side of the compressor after first experimenting with a location directly in the return line from the chamber which caused the pressure controller (10) to oscillate. Figure 3 shows the measured exhaust flow with time. One clearly sees that the flow rate is too small for the used pressure regulator which causes alternating closed and open states of the control valve. The system can nevertheless be operated since the resulting small pressure fluctuations in the big loop proved to be varying slowly enough to be irrelevant.
It should finally be noted that the pressure controller (10) regulating the chamber pressure has to operate on a quite low pressure drop of a few 100 mbar maximum across the device. The same holds for the MFC (6), which has been bought in a special low Δp version[14]. Operating the compressor such that the system is at 3.2 bar (abs.) on the high pressure side and on 2.9 bar low pressure side of the pump has turned out to be best suited for stable conditions and lies well within the operating range of the ATC (table 2).

Operating multilayer 1 in flushing mode

As mentioned above, it is also possible to operate the normally circulated part of the gas system in single pass mode. In this condition the fresh gas intake has to be increased by typically a factor 10. The only other necessary change is a lowering of the setpoint of pressure controller (11) in the exhaust line from typically 3.2 bar to around 2.8 bar to allow

[13]model as [12]
[14]model F-111C-FAC-33-V, Voegtlin Instruments AG, Aesch, CH

for the necessary pressure drop across the chamber pressure regulator (10). Operation in flushing mode without the need for any hardware change on the setup was e.g. taken advantage of during the testbeam operation in June 2002 due to problems with induced electrical noise created by the ATC frequency controller (see section 4).

System behaviour in case of circulation failure

The behaviour of the gas system in case the gas circulation fails needs some careful advance consideration, mainly due to the often unsupervised, longterm continuous operation of the setup. In case the flow in the big loop is stopped, the pressure difference between low and high pressure side of the compressor cancels. Since the pressure drop in the big loop almost completely occurs across the strangulation valve (15), the main part of the loop is normally at ≈2.9 bar. Since gas will only be released from the system to exhaust by the controller (11) when a pressure of ≈3.2 bar is reached, the pressure in the circuit will start to rise slowly up to this value due to the uninterrupted fresh gas intake. The pressure in the BIS chamber will initially stay at the standard 3 bar, until the pressure drop across regulator (10) falls below the minimum needed 50 mbar or so due to the overall system filling up. If the stop in circulation is not detected by then, the whole system (big loop and chamber) will stabilise at a total pressure of 3.2 bar, which is uncritical for MDTs which have to stand up to 4 bar according to the Atlas safety and quality control specification [6]. For further protection self-releasing overpressure valves (set to open at 3.5 bar) have been included in the circuit at the chamber inputs.

Before the system can be restarted after a (long) circulation failure, some gas has to be released from the system to bring the big loop back into the operation regime of the ATC. Since non-adherence to this will damage the compressor, the in- and output pressures are checked by the computerised control and monitoring system (section 3) before allowing a restart of the circulation.

Analysis and monitoring equipment

Several instruments to analyse and monitor the gas composition and to facilitate the detection of any changes have been included in the prototype system, namely two devices for monitoring the water content in the gas as well as a device for measuring oxygen. Water and oxygen levels are measured in a special analysis line which can alternatively receive gas from either of the two chamber multilayers or directly from the premix supply. The water content is obtained using a moisture meter model SDA[15], which deduces the H_2O concentration from measuring the humidity dependent dielectric constant of a special analysis cell. Oxygen is monitored using an instrument Teledyne 316A-2X[16] with a zirconium cell A-2C suitable for use with CO_2 containing gas mixtures.

Since especially the water measurement turned out to suffer from the low available flow (which goes to exhaust and is thus "lost" from the circulation loop), a second device, model 2000 Series DewPrime by EdgeTech, Milford, US, measuring directly the dew point[17] in the circulating gas at 3 bar was installed into the system just in front of the chamber pressure regulator (10).

[15] Shaw Moisture Meters, Westgate, UK

[16] Teledyne Analytical Instruments, Los Angeles, US

[17] The dew point is the temperature at which water can exist in equilibrium in both vaporised and liquid state. This temperature is measured by cooling down a mirror in the gas flow until water condensates on its surface, a condition which is detected by a change in the reflectivity for light

Finally a connection to sample the gas composition with a mass spectrometer previously used in various testbeam studies is available.

3 Control and Monitoring System

Since the planned operation at GIF of the prototype system was from the beginning foreseen as a longterm ageing study, precautions had to be taken to allow the system to run without continuous presence of personnel. A dedicated monitoring and control system has thus been developed, which shall be described in the following paragraph. The system, often also called "slowcontrol", has the double job of

a. Monitoring and recording all slowly varying parameters of the system needed for a later analysis of the (ageing) data. The interval between measurements for this purpose is usually chosen on the level of some minutes.

b. Continuously checking for any anomalous and potentially dangerous conditions in the system, i.e. in the described setup mainly in the pump circuit. Such a fault might cause damage very quickly (imagine e.g. a serious gas leak in the big loop, such that the minimum necessary pressure at the input of the ATC would no longer be sustained with the consequence of a damage to the gas bearings of the compressor) and thus has to be detected very quickly, certainly on a time scale far smaller than the standard parameter recording for later analysis.

For all of the slow control tasks LABVIEW 6i from National Instruments has been used as development environment. This platform was preferred to the PVSS package, which is the default for slow control matters within the LHC detectors, as it provides a faster, more straight forward approach for implementing the needs of a prototype like the one described here. 3 separate, stand alone applications have been implemented; the first handles control of the ATC pump while the second deals with the monitoring data from the various devices in the gas system. The third program (which is not further described in this note) allows to easily visualise the development of all recorded parameters with time.

Pump control

The main purpose of the pump control program (`MDT_pump.vi`[18], figure 4) is to allow a secure and stable operation of the ATC under different rotation speeds according to the safety measures stated by the manufacturer. Some of these precautions can be covered by the frequency controller[19] supplying power to the ATC, itself. The following parameters, stored in the flash memory of this general purpose motor control device, have been configured to the corresponding limits:

a. **minimal operating speed:** 40 000 rpm

b. **maximal operating speed:** 52 500 rpm

c. **acceleration ramp:** 2 s/100 Hz

d. **deceleration ramp:** 1 s/100 Hz

[18] a single program or subprogram is called VI (Virtual Instrument) in the concept of LABVIEW

[19] UNIDRIVE 1404, Control Techniques Drive Ltd., UK

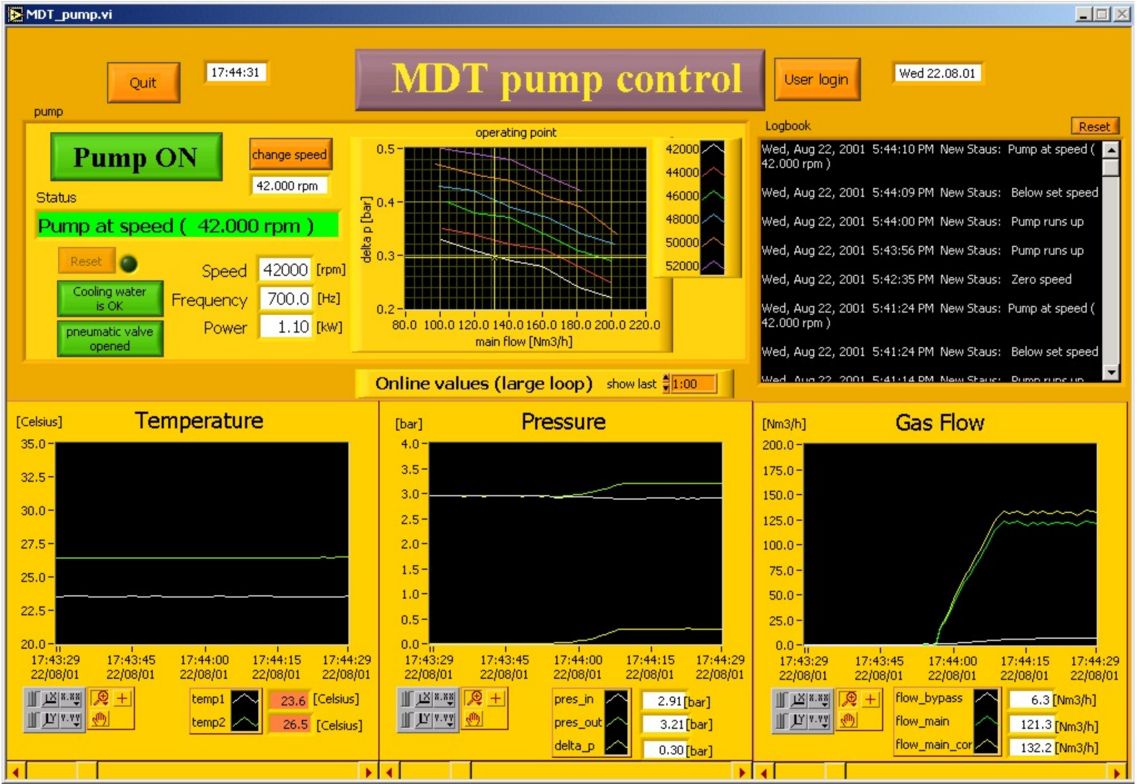


Figure 4: Screenshot of the MDT_pump panel for controlling the ATC

e. **electric current limit:** 1.5 $\times$ nominal current = 6.8 A

f. **overheating of the motor coils:** There are two PTC-thermistors installed in the stator windings, which let the frequency controller trip whenever the temperature exceeds a threshold around 140 ^{o}C.

g. **sense of rotation:** As the gas bearings would be destroyed quickly whenever the motor shaft is driven in the wrong direction, the frequency controller was forced by a internal flag to permit only the design sense of rotation (clockwise seen from the wheel blade side). Nevertheless attention has to be paid not to swap the electric phases whenever recabling of the electrical supply becomes necessary.

All the other critical quantities for running the ATC without risking any serious damage are continuously checked by the pump control software. Since ProfiBus modules, as the frequency controller is one, keep their state also in the case of stuck communication, a hardware watchdog was implemented into the SCADA[20] system, to prevent the pump from keeping on running although the control PC already crashed. Therefore the control program has to toggle a digital output within a certain time period (now set to 3 seconds) to retrigger the time of a mono flop, otherwise a relay opens, leading to an external hardware trip of the frequency controller, which immediately shuts the pump down. A further safety advantage of the watchdog is that without starting the control program sending its watchdog signal the frequency controller is locked, therefore the ATC can not be launched unintentionally. Using the watchdog another safety mechanism was implemented into

[20]Supervisory Control and Data Acquisition

the control software: Whenever a missing acknowledge for a shutting down command is observed, the program simply quits itself so that the hardware watchdog in series will turn off the ATC in any case.
So all remaining safety issues concerning the pump can be monitored by the slow control software without any undesired effects in case of a software crash. The Program `MDT_pump.vi` is responsible for watching the

a. **inlet and outlet pressure** within the pump circuit: Both, a too low and a too high pressure will cause harm to the ATC. A low pressure leads to vibrations which quickly will damage the gas bearings and the blade wheel beyond repair, whereas a too high pressure overloads the bearings. For this reason the in- and outlet pressure is restricted with a software interlock to values between 2.7 and 3.4 bar during operation and has to stay between 2.8 and 3.1 bar before launching the ATC.

b. **minimum gas flow:** if the gas flow falls below a certain limit, dependent on pressure and rotation speed, instabilities in the domain of the gas bearings occur, leading again to vibrations and damages. To be safely away from this so called surge region (see also figure 7) a software interlock forcing a minimal flow of 90 Nm^3/h was implemented which is activated time delayed after the pump reaches its final speed. In principle it could help within a limited range to react on a critical low flow situation by increasing the rotation speed or via closing a motor-actuated bypass valve. For this prototype it was preferred to immediately switch off the ATC in such a case.

c. **cooling water flow rate:** The chassis around the stator of the circulator is surrounded by cooling pipes. The ATC manufacturer states that for a permanent operation a minimum cooling water flow of 1.5 l/min of 20 ^oC warm water is mandatory. Therefore the threshold of the used water flow monitor[21] was set to about 2 l/min. Moreover it should be mentioned that the flow monitor is situated at the cooling water outlet side to avoid a misinterpretation of the cooling status whenever a cooling water loss takes place on the way from the flow monitor to the pump.

d. **frequency controller status:** For further security the control program will stop the ATC when an abnormal status word is read out from the frequency controller, even when the causative status bit would already lead to a trip of the drive by itself (e.g. status bits "load reached", "in current limit").

Besides observing the parameters above, the pump control program logs all its error messages and also every change of the UNIDRIVE status to the screen and to a log file. Furthermore the operator gets informed via email and SMS whenever the pump is unexpectedly shut down (this is obviously not possible in the case of a power cut).

Slowcontrol monitor

The stand alone program `MDT_monitor.vi` (figure 5) gives a clear overview about the current state of the whole gas system with all the measured flows, pressures and temperatures and moreover shows other slow control measurements like high voltage, temperatures measured on the chamber and readings from gas analysis instruments (oxygen and water

[21] Eletta V1-GL15

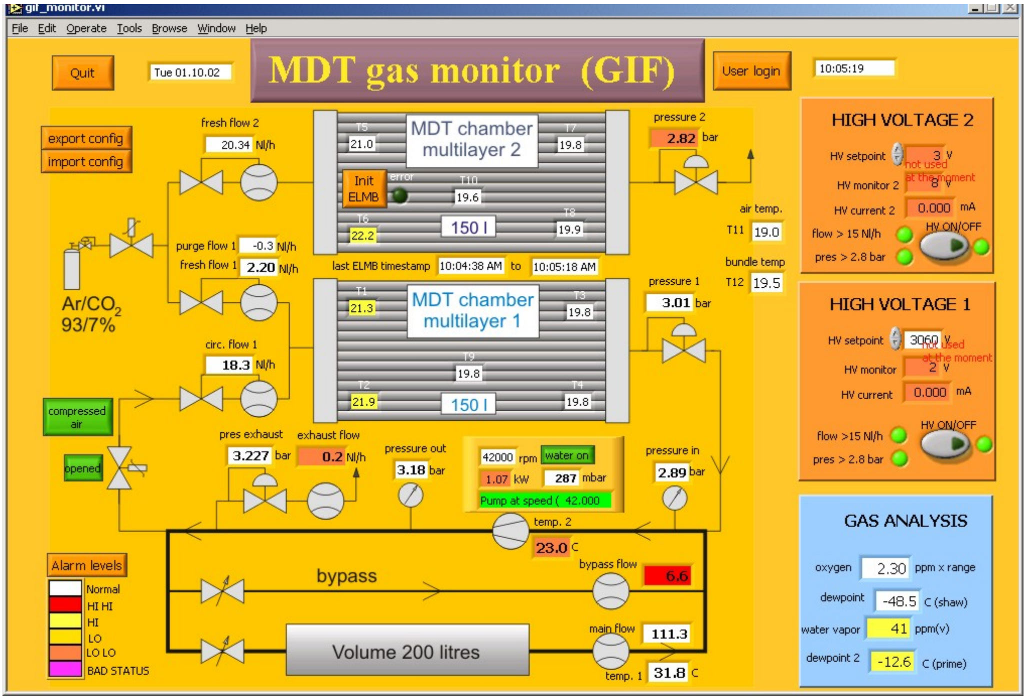


Figure 5: Screenshot of the MDT_monitor panel showing the momentary status of the full gas system

meter). Each of these 38 slow control channels is stored every minute into an ASCII-spreadsheet file, which is transferred once per day to one of the PCs running the BIS chamber DAQ and from there to the CERN Central Data Recording facility CDR.

Slowcontrol DAQ

The architecture of the slowcontrol DAQ (figure 6) is based on the I/O field bus system 750 from the company WAGO. All interface modules[22] are plugged in rail-mounted terminal blocks. This modularity, the flexibility to interface to any of the common field busses (CAN, Ethernet, Interbus, Modbus, Profibus) by just changing the fieldbus controller, plus the economical price have been the main criterions why the CERN Gas Working Group recommended this system. The resolution of the analog in- and output channels is with 12 Bit and a measuring error of 0.2 % with respect to full scale acceptable for the measurements of this application.
As field bus system the Profibus was chosen, to which also the frequency controller (Unidrive 1404) is connected as a separate station. One digital output of the WAGO system was used to retrigger the self made watchdog in regular intervals to avoid an external trip of the Unidrive. The Profibus is controlled by an applicomIO card sitting as PCI card in the slowcontrol PC. Since for the readout of the chamber temperature with PT-100 sensors an ELMB [23] was selected, a CAN bus had to be integrated into the DAQ,

[22] for this setup 4 analog input modules 750-468 (0...10 V), 1 analog output module 750-550 (0...10 V), 1 analog input module 750-454 (4...20 mA), 1 digital input module 750-402, 1 digital output module 750-504 (24 V) and 1 module 750-461 for reading 2 PT-100 temperature sensors have been installed, www.wago.com

[23] Embedded Local Monitor Board, LHC experiments custom design

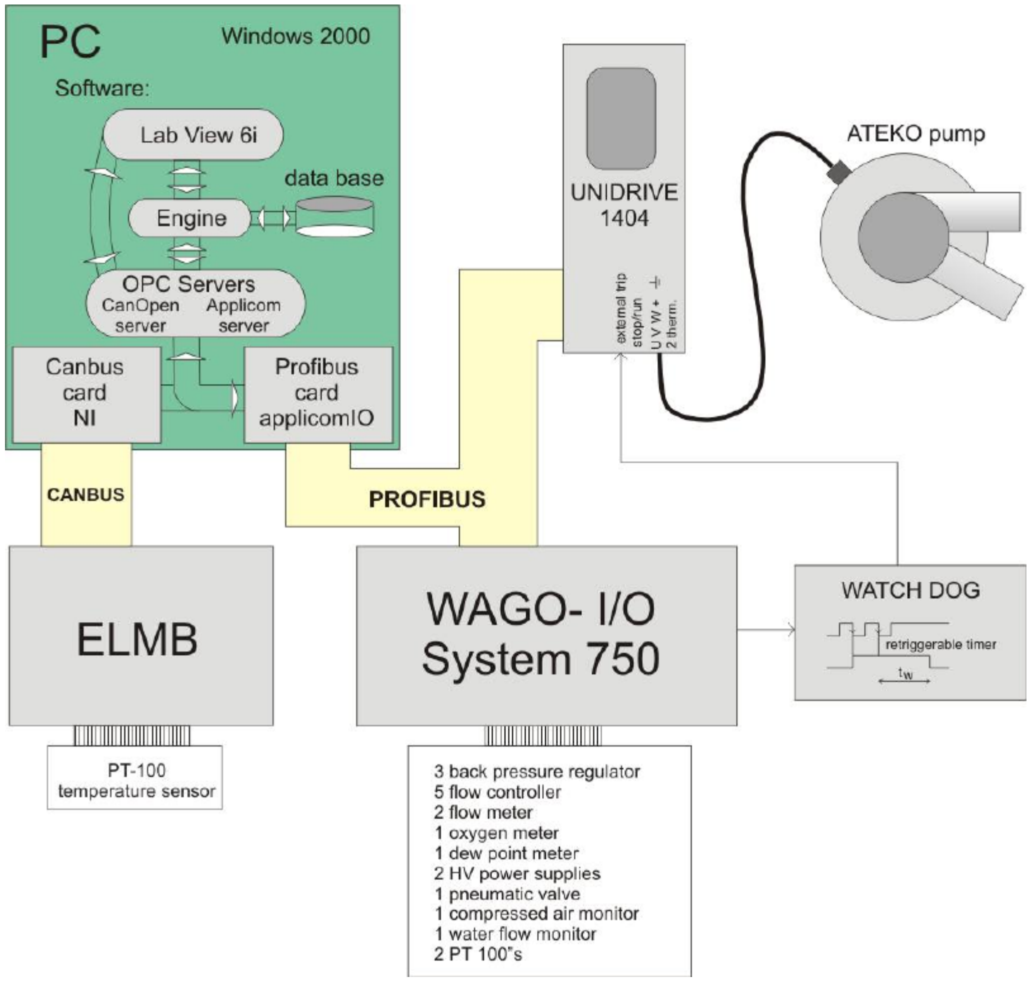


Figure 6: Block diagram of the slowcontrol DAQ

managed by a Canbus card[24]. Both field bus controllers are communicating via their OPC[25] servers (Applicom server and CanOpen server) with the so called Engine. The Engine is the server of LABVIEW 6i which keeps the handling of the I/O-items, like updating their values, converting them from raw to physical relevant values, generating alarms, recognizing access levels of users and so on by autonomous processes in the background. In this way the items of many different hardware drivers are available in a uniform and manageable manner within the slow control application.

4 Measurements and first experience with the prototype system

Gas flow versus pressure difference created by the ATC

When discussing the relation between a given flow rate through a system and the pressure drop Δp necessary to sustain it, the two limiting cases of laminar and turbulent flow

[24]National Instruments
[25]OLE for Process Control, whereas OLE in turn stands for Object Linked Embedded

behaviour have to be distinguished. This stems from the fact that the resistive forces (friction) affecting the free flow of viscous fluids are highly dependent on the flow regime. For laminar behaviour the fluid can be thought of as a set of different layers which move against each other without intermixing, while turbulent behaviour is characterised by the random displacement of finite mass elements of the fluid which mix strongly with each other. To quantify the level of turbulence the dimensionless Reynold number Re can be used:

$$Re = \frac{\rho w D_h}{\eta}, \tag{1}$$

where ρ is the density, w the stream velocity, D_h the equivalent diameter and η the dynamic viscosity[26]. For a given setup there is a range of critical Reynold numbers in which the transition from laminar to turbulent flow behaviour takes place. For circular pipes the lower limit of this transition region is at a Reynold number of approximately 2300 [8]. In our case[27] the Reynold number of the flow in the "big loop" is around 50 000, thus in the highly turbulent regime, whereas a Reynold number of about 150 in the pipes supplying the chamber indicates a quite laminar behaviour.

The pressure drop needed to achieve a certain flow rate can in the general case be expressed as the sum of two terms which are proportional to the first and second powers of the velocity of flow w [8]:

$$\Delta p = k_1 w + k_2 w^2. \tag{2}$$

At very low Reynold numbers ($Re < 25$) the second term can be neglected, leading to the well known law of Hagen-Pouiseuille, while at very large Reynold numbers ($Re > 10^5$) only the quadratic term contributes.

A set of such Q_{flow} versus Δp curves, defining the characteristic of the ATC, were measured for the "big circulation loop" of the prototype system and can bee seen in figure 7. The six graphs with rather small slope where taken at a fixed rotational speed of the compressor, with different flow rates achieved by adjusting the manual valve (15). The four curves with steep slope were on the other hand taken with a constant flow restriction (manual valve setting fixed). This is the situation described by equation 2. One sees that for a fixed resistance in the system, i.e. fixed so called K_V value, the pressure difference needed to be built up by the compressor increases strongly with the delivered flow. Reachable flow rates are restricted by the limit on the power of the pump motor. A careful look at figure 7 also shows the major contribution of turbulent flow behaviour, since an extrapolation to the measured points using only the linear part of equation 2, $\Delta p \sim w \sim Q_{flow}$, would intersect the horizontal (flow) axis at values far to the right of zero flow, as one expects when approximating a parabola by a tangent to one of its points, see figure 8.

The importance of the compressor characteristic lies in the fact, that for the later Atlas gas system one usually specifies the overall flow rate, at present to 1 volume exchange per day but with some still ongoing discussion. Given the resistance of the system, figure 7 yields the needed pressure difference, which can be generated by adjusting the rotational speed of the compressor. Without changes in the system resistance (K_V-value) the band of accessible flow rates is severely limited by the power and surge limits. The range can be extended, if in addition to the pump speed the system resistance can be adapted, e.g. if a significant part of the overall pressure drop occurs across an adjustable throttle valve.

[26] η is the ratio of the shear stress τ to the velocity gradient normal to the direction of fluid motion, i.e. $\eta = \frac{\tau}{dw/dy}$

[27] $Ar{:}CO_2$ (93:7) at 3 bar and 30 ^{0}C $\Rightarrow \bar{\rho} = 4.79\,kg/m^3$ and $\bar{\eta} = 22.2\,10^{-6}$ Pa s, $D = 50\,mm$, volume flow $Q = 100\,Nm^3/h$, $w = \frac{4Q}{p/p_0 D^2 \pi} = 4.7\,m/s$

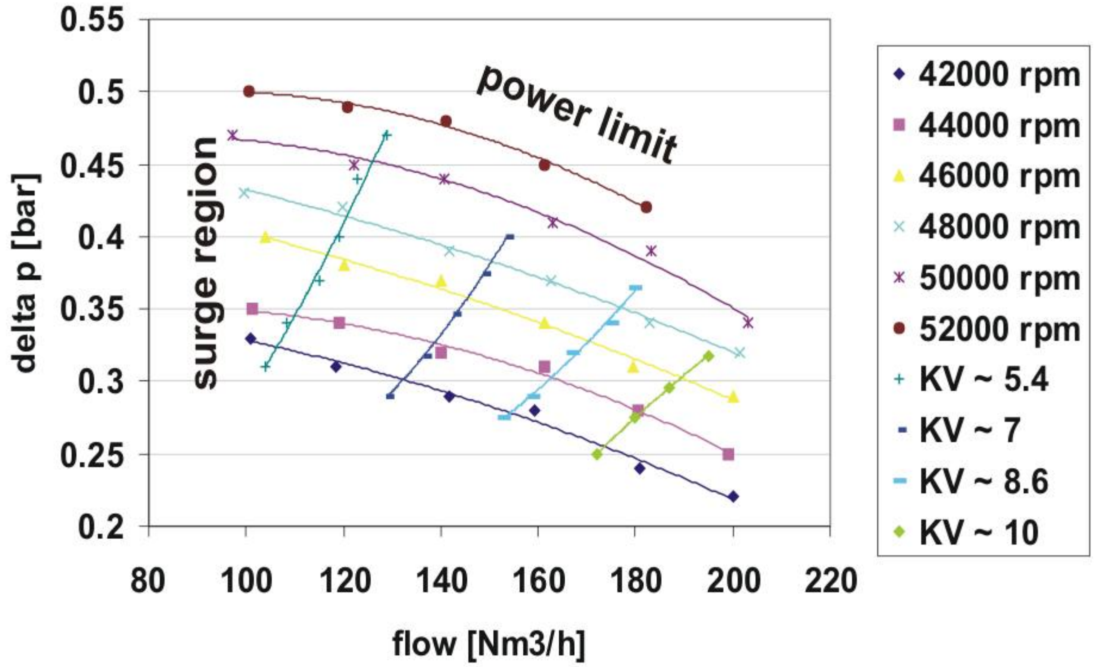


Figure 7: flow-Δpressure characteristic of the ATEKO Turbo Circulator. For the graphs with fixed rotational speed of the pump the resistance in the system was varied with valve (15); for the curves with fixed K_V value the valve settings was left unchanged but the pump speed was varied instead.

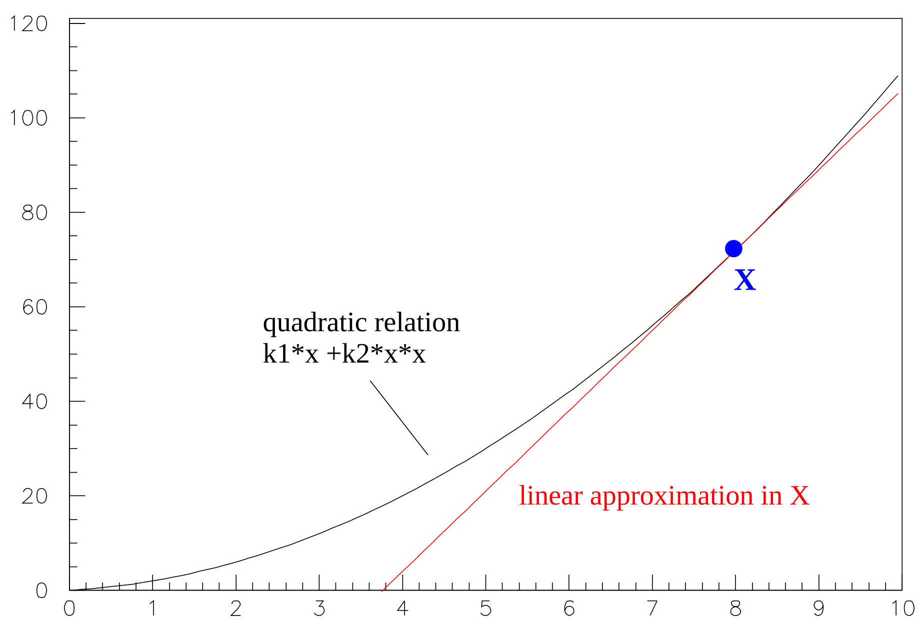
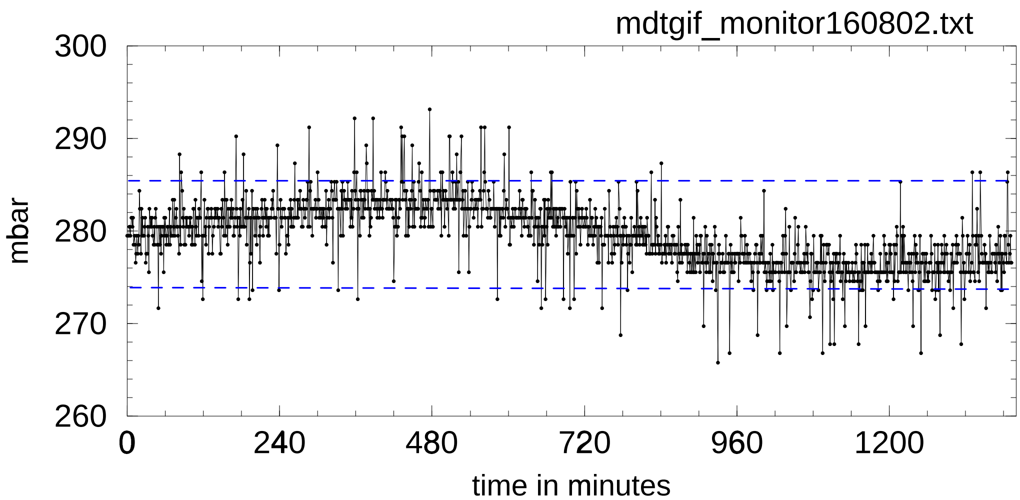


Figure 8: Interpretation of figure 7: The approximation of a quadratic relation by the tangent in a point X leads to a positive intersection with the x-axis.

Pressure and flow stability

The most important system parameters in terms of stability are the flow and pressure in the main circulation loop. Figure 9 shows the pressure drop across the compressor as well as the measured gas flow rate in the big loop over the course of 24 hours. One can see that both quantities stay constant within 3 (Δp) and 1 percent (flow) correspondingly which is adequate for the later Atlas operation.



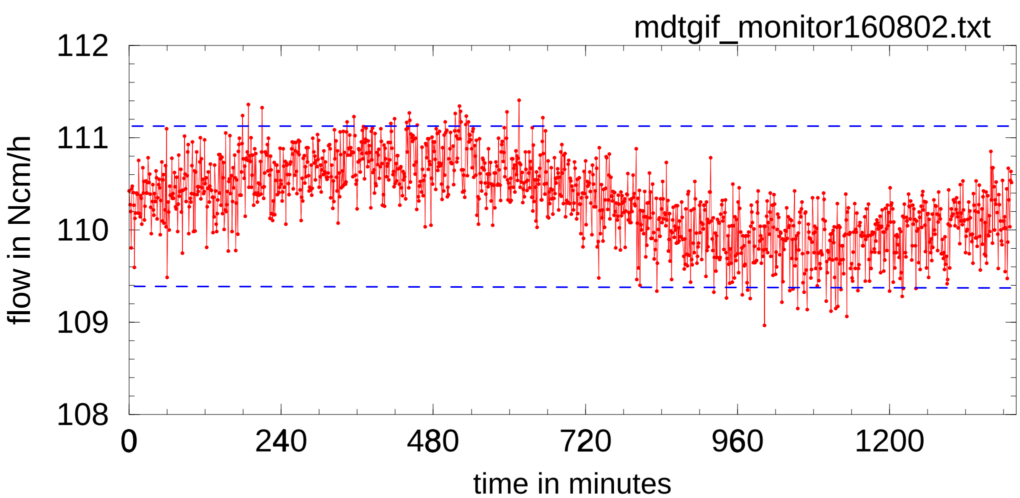


Figure 9: Measured pressure difference between in- and output of the ATC (top) and gas flow rate (bottom) in the "big" loop over 24 hours. The stability is, except for isolated points which are most likely noise spikes on the analogue slowcontrol readings, better than $\approx$ 3% for Δp and better than 1% for the flow rate. Pump operation was at 42000 rpm.

Electromagnetic compatibility and induced noise

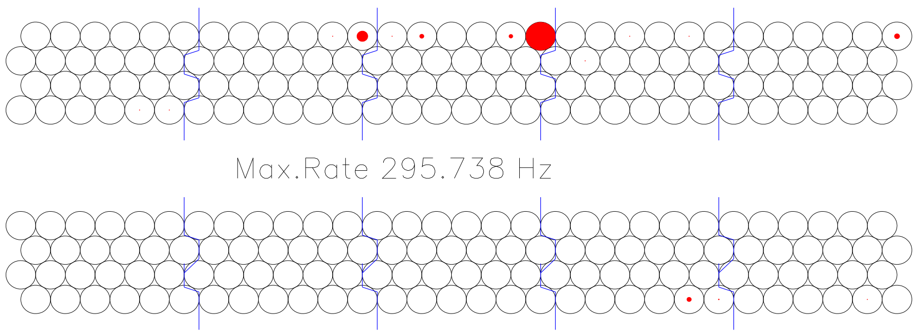
As mentioned before, power to the Ateko compressor is supplied as alternating 3-phase current with a frequency equal to the angular frequency of the turbine (up to 55000 rpms) via a special controller type UNIDRIVE UNI 1404 manufactured by Control Techniques

action	mechanism	importance
Mount controller on sturdy metallic back plane , Earth separately	Grounding	***
Use a special RF filter, type 4200-0010, Control Techniques Drive Ltd, in the AC supply to suppress propagation of noise spikes over AC network and power GND [28]	Filtering	*
Connect controller and pump motor using a cable with a metallic shield. [7]	Shielding	***
Connect the cable shield solidly to Earth (back plane) **within 10 cm of the controller** [7]	Shielding	*****
Avoid any coiling up of spare cable length between controller and motor	Limit e.m. emission	**
Decouple the metallic gas pipes from the chamber by insulating pieces **both at the chamber input and between gas rack and piping**	Limit noise propagation	***
Install the foreseen Atlas MDT RC-filter circuit in the chamber HV supply line close to the chamber	Filtering	**

Table 3: Actions taken to reduce the problem of induced electric noise caused by the ATC

Drive Ltd., UK. This Universal Variable Speed Drive operates on the standard $3 \times 220\,\mathrm{V}$ industrial electrical distribution.
The combination of high power (up to 2.5 kW, table ,2) alternating currents in the kHz domain together with the highly sensitive MDT front end electronics where un-amplified signals are in the μV range turned out to be problematic. The first time the chamber was operated together with the gas circulation running in November 2001 the situation was indeed so bad that basically all 240 drift tubes were oscillating with amplitudes well above the threshold of 60ṁV at the output of the front end electronics amplifier. Reading out the chamber at all proved impossible.
Various approaches to reduce the amount of induced electrical disturbance were tested and an effort was made to actually understand the way noise was induced onto the BIS chamber. The second point seemed especially important since discussions with the manufacturer of the UNIDRIVE frequency controller showed that all such devices were prone to high electromagnetic emission, thus implying a non-negligible risk for the later Atlas operation.
Table 3 summarises the actions taken to eliminate or at least reduce the induced noise problem to an acceptable level. The list does not claim to be exhaustive, but should rather serve as a starting point for later or similar planning. Last but not least we would like to mention that the Atlas MDT setup was not the only one effected at GIF when the gas circulation was running, but rather that also CMS ECAL was heavily compromised in the beginning.

[28]The RF passive filter works by dissipating spike currents up to 7 mA directly to GND. This puts some strain on the otherwise balanced 3-phase supply. It was further observed that the current was enough to



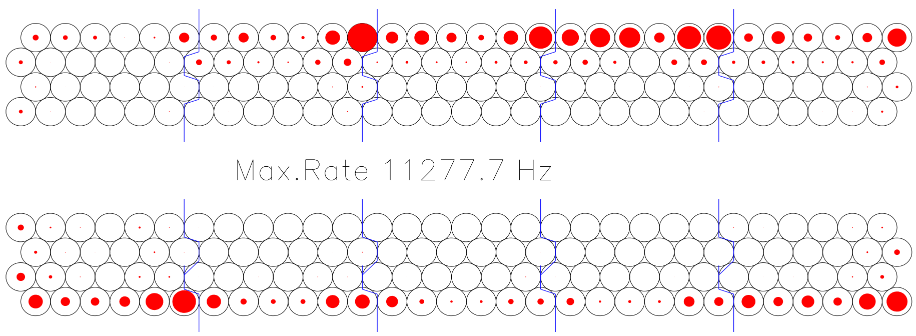


Figure 10: Measured single tube noise rates at nominal threshold (60 mV) with the ATC switched off (top) and running (bottom) after the electromagnetic emission had been reduced by the methods described. The area of the filled circles is proportional to the measured count rate.

Figure 10 shows measured noise rates on the BIS drift tubes at nominal threshold with the circulatory gas system switched on and off, after the described actions to reduce the electromagnetic emission were applied. One clearly still sees a significant difference, especially in the outer tube layers which act as shielding for the inner layers.

Way of noise penetration onto the BIS chamber

One is tempted to think that the problem with electromagnetic emission by the ATC/controller will not manifest itself in the later Atlas setup due to the large spatial distance between gas system (surface building) and detector (cavern). This is certainly true if noise is induced on the chamber by direct electromagnetic radiation through the air, but is less obvious if electric disturbances travel via conducting materials and/or the earth connections. For the prototype system at GIF the X5C gas zone refurbishment in February 2002 gave the opportunity to in situ investigate the means of noise propagation; the following was found:

- A propagation via the 220V/380V GND is unlikely; connecting the gas system to a different electrical supply from the chamber electronics did not improve the situation.

regularly trip the standard FI protection device in the 220V/380V line, which had to be taken out.

- With the metal pipes between gas zone and GIF area ($\approx$ 20m distance) removed no difference in measured noise rates could be observed when switching the ATC on and off.

Our conclusion is that the dominant mechanism of noise propagation is via the conducting gas piping, from where it is transmitted via electromagnetic radiation (antenna effect) to the chamber. A direct contact between chamber and gas lines is excluded via the used insulated decoupling pieces at the chamber input. Since disturbances distributed via conducting materials do not necessarily scale down with distance, the question of electromagnetic compatibility (EMC) should indeed be taken seriously also for the final Atlas installation.

5 Outlook

This note described the prototype setup of the Atlas MDT circulatory gas system. The system has been under continuous operation in circulation mode for a period of 2 months between March and May 2002, after which the BIS chamber was used in the more simple one-pass mode for 2 weeks of high γ-background testbeam studies. The 2 month period did allow a first evaluation of the system mainly in terms of stability and robustness. The setup will be recomissioned at GIF after this year's SPS beam operation finishes to complete the ageing part of the planned measurement program.
One effect observed but not presented in this note is a continuous increase in the measured maximum drift time in the multilayer under gas circulation with time. The effect is seen both with and without irradiation. The suspected cause is a gradual accumulation of water in the gas, either from desorption from the tube walls or from diffusion into the system. Further studies are needed to definitely exclude other contaminants and to determine how the drift behaviour of the gas can be stabilised. This topic will also have to be addressed together with the question of any artificial addition of water into the gas system as is envisioned for reasons of HV stability.

6 Acknowledgements

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We would further like to thank our Greek colleagues for providing the BIS module zero chamber for this test, William Andreazza for all kinds of technical support and our co-users at GIF for their sometimes hard pressed patience.

References

[1] F. Hahn, S. Palestini: *The MDT Gas System, a Design Report*, Atlas Internal Document, Geneva June 2002

[2] S. Kircher, M. Kollefrath. G. Herten, W. Mohr, W: *Parameter of MDT Ageing and Reanimation*, Atlas Internal Note ATL-MUON-2001-012, Geneva, September 2001

[3] V. Paschhoff, M. Spegel: *Ageing studies for the ATLAS MDTs using Ar-CO2 90-10*, Atlas Internal Note ATL-MUON-2000-004, Geneva, June 1999

[4] ATC a.s.: *Argon-Turbo-Circulator, Technical Description and Service Instructions*, Hradec Králové, Czech Republic, February 2001

[5] G. Kaptis, C. Petridou, I. Tsiafis, J. Wotschak: *Mechanical design of the BIS module zero MDT chamber*, Atlas Internal Note ATL-MUON-98-242, Geneva, June 1998

[6] H. Kroha: *Quality Assurance and Control Reference Document for ATLAS MDT Chmaber Construction*, Atlas Internal Document version 1.1.3, Geneva, May 1999

[7] Control Techniques Drives Ltd: *Unidrive, Unidrive VTC, Unidrive LFT Installation Guide*, Part No 0447-0088, Issue 5, September 1998

[8] I.E. Idelchik: *Handbook of Hydraulic Resistance*, CRC Press, ISBN 0-8493-9908-4, 3^{rd} edition, Moscow, 1994