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Leak Detection

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LEAK DETECTION

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Abstract
This paper will give an introduction to the leak detection of vacuum systems. Various methods to detect leaks as well as the most widely used helium leak detectors and its different applications are presented. Practical examples in the context of accelerator vacuum systems will illustrate the topic.

1. INTRODUCTION

Ideally a vacuum chamber should maintain the achieved vacuum pressure forever after switching off the pumps. However without active pumping the pressure in a real system will rise with time. This pressure rise is produced by outgassing – the spontaneous evolution of gas molecules from the walls – and gas molecules penetrating through leaks and entering by permeation from the outside into the vacuum system. Figure 1 shows three typical curves for the behaviour of the pressure increase as function of time on a linear scale: outgassing starting with a linear pressure increase und levelling off once outgassing and vapour pressure reach equilibrium, the linear increase due to a leak and the combined curve of the two effects.

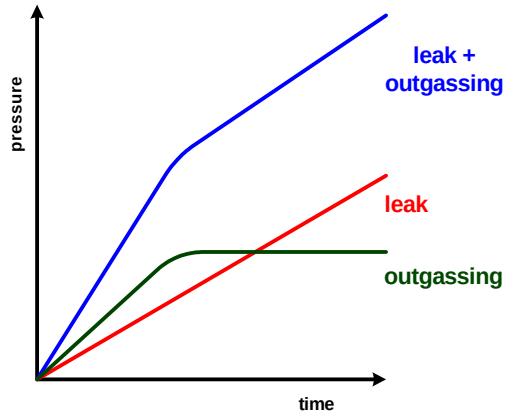

Fig. 1: Pressure increase due to outgassing, a leak and the combination of outgassing and a leak.

In practice it is impossible to build a completely leak tight vacuum system. And this is even not necessary. On the other hand the leak rate must be small enough not to prevent to reach the required pressure level. Therefore it is important to specify an acceptable leak rate for each vacuum system. After manufacturing of a vacuum vessel is must be proven that the tightness specifications are fulfilled. Further checks are necessary during as well as after assembly and installation to locate possible leaks created during the previous steps. Thus leak detection is an important step in the production of vacuum to guarantee that the required pressure and gas composition conditions of a vacuum system can be reached. Adequate methods and leak detection equipment have been developed over the past decades following the ever-increasing demands by industry.

This lecture will start with some introductory remarks about leak rates and leak types followed by various leak detection methods. The most widely used helium leak detectors and its different applications will be described in detail. This will be illustrated by practical examples in the context of accelerator vacuum systems.

2. LEAK RATE

The leak rate is defined as the *pV*-throughput of a gas through a leak. It is a function of the type of gas, pressure difference and temperature. In a system of volume V the leak rate Q_l is given by

$$Q_l = V \cdot \frac{\Delta p}{\Delta t} \ . \tag{1}$$

Here Δp is the pressure rise during the time interval Δt. Commonly used units for leak rates and its conversion factors are given in Table 1.

Table 1
Conversion factors for leak rates in various system units [1].

	mbar·l/s	Torr·l/s	Pa·m^3/s	cm^3/s*
mbar·l/s	1	0.75	0.1	0.99
Torr·l/s	1.33	1	0.133	1.32
Pa·m^3/s	10	7.5	1	~10
cm^3/s*	1.01	0.76	0.101	1

* STP - standard temperature and pressure (0^oC, 1 atm)

As an example, for a high vacuum (HV-) system one can take the leak rates given below as a rule of thumb:

- $Q_l < 10^{-6}$ mbar·l/s: very tight system,
- $Q_l < 10^{-5}$ mbar·l/s: tight system and
- $Q_l < 10^{-4}$ mbar·l/s: leaky system.

The following examples illustrate the relationship between the size of a pore, the corresponding leak rate and the amount of gas entering into a vacuum system. For simplification it is assumed that the pore is a straight channel of circular shape. A diameter of 0.01 mm, e.g. a hair, corresponds to a leak rate of 10^{-2} mbar·l/s. For a pore with a leak rate of $Q_l = 10^{-10}$ mbar·l/s = 10^{-10} cm^3/s an amount of 1 cm^3 of gas needs 317 years to flow through the leak channel.

3. LEAK TYPES

Leaks may appear by various defects within the material and/or at connecting areas:

- fixed connections by brazing, welding or gluing – especially transitions between different materials like glass-metal, ceramics-metal, etc;
- pores and hair cracks due to mechanical or thermal stress, which to some extend are always present and therefore must be small enough in size and number such that they do not disturb;
- flanged connections;
- cold/warm leaks opening up at extreme temperatures – often being reversible;
- virtual leaks, where gas is evaporating from inner excavations, dead holes etc., leading eventually to long pumping times (see sub-section 8.1) and
- indirect leaks from supply lines for e.g. cooling water or gas/liquids (He, N_2) of cryogenic systems.

A leakage, but not a leak due to a defect is the

- *permeation*, i.e. the natural porosity of material.

The permeation could be quite significant and even limit the detectable leak rate. For example, at HERA large amounts of Perbunan® rubber seals with a permeation rate of $2 \cdot 10^{-2}$ mbar·l·mm/s/m^2 are used at the insulating vacuum tank resulting in a total permeation rate of $2 \cdot 10^{-5}$ mbar·l/s/m [2].

This long list shows that already during design and manufacturing great care is necessary to avoid potential leaks.

4. LEAK DETECTION METHODS

The aims of a leak search are to localize a leak and/or to determine the total or local leak rate. Depending on the size of the leak, various effects can be used for leak detection. All methods are based on the variation of a physical property measured on one side of the vessel while the pressure or the nature of the gas is changed on the other side. Large leaks can generate mechanical effects as described in sub-section 4.1, while smaller leaks require more sophisticated methods (see sub-sections 4.2 and 4.3). A detailed list of possible leak detection methods, their sensitivities and references can be found in Ref. [3]. A comprehensive review of leak detection methods and apparatus is given in Refs. [1] and [4-5].

4.1 Mechanical effects

Methods applying measurable mechanical effects are limited to large leaks. For example ultra sound detectors may be used to monitor the oscillations produced by the gas in the vicinity of a leak. The detection limit of this method is limited to leak rates of 10^{-2} mbar·l/s. Somewhat more sensitive is the formation of bubbles when water or even soaped water is spread on a leak with the vessel being pressurized to over pressure. A sensitivity of 10^{-4} mbar·l/s can be reached.

These methods are simple, very quick to carry out, cheap and one can locate a leak. However due to the limited sensitivity they are restricted to the high-pressure region.

4.2 Pressure increase

In approaching the problem of a supposed leak larger than the admissible value, it is necessary to determine first if such a leak actually exists. Taking curves of the pressure versus time as shown in Fig. 1 will assist in determining if there is a leak and estimating the actual leak rate. First the system is evacuated to a stable minimum pressure. When no further improvement in the pressure is evident, the pumps are switched off or separated from the system. There will always be an initial pressure rise due to outgassing, thus one will have to wait sufficient time until outgassing has come to equilibrium with the vapour pressure in the gas phase. In case of a leak the pressure will continue to increase linearly with a different gradient instead of levelling off. The pressure curve should be taken till the shape of the curve becomes evident. More details might be found in Refs. [3] and [6].

However it requires a lot of experience to reliable analyse such curves during initial pump down with still a lot of outgassing or in the presence of virtual leaks. Here the application of a liquid nitrogen trap might be useful to minimize the effect of the vapours present in the system. Small leaks might not be visible with this method. In any case additional methods as described in the following sub-section need to be applied for further diagnosis.

4.3 Modification of the physical properties of the residual gas

By changing locally the air composition in the vicinity of a leak by adding a gas (*the tracer gas*), the composition of the residual gas and thus its physical properties are modified. As accurate and sensitive measurement methods for many physical gas properties are available measuring these alterations can be used to determine the position and size of a leak. The sensitivity of such methods is sufficient to detect even quite small leaks. In the following the most widely used methods are shortly described.

The variation of the heat conductivity can be detected using a Pirani gauge and alcohol, CO_2 or helium as tracer. The pressure will rise in case of helium, otherwise drop down. Using (heavy) noble gases, the change in ionization cross section can be monitored by the signal of an ion gauge or even a sputter ion pump. A nice example of this method is described in Ref. [7].

Analyzing the mass of the residual gas is the most sensitive and widespread method in locating leaks. Using an optimized mass spectrometer and helium as tracer gas, leak rates down to 10^{-12} mbar·l/s can be detected. A more detailed description will follow in section 5.

4.4 Tracer Gas

The tracer gas should have the following properties:

- unambiguous signal in the mass spectrum of the residual gas;
- chemically and physically inert, non explosive and cheap;
- very low content in air and
- easily removable by pumping and not contaminating the system.

Helium is most commonly used fulfilling all conditions mentioned above. Therefore the leak rate is usually given as helium standard leak rate (He Std) assuming a pressure difference of 1 bar from air to vacuum. The small diameter of the helium atoms allows the detection of very small leaks. As the speed of helium is three times higher than the speed of air, the amount of helium entering through a leak and thus the sensitivity is increased by a factor of 3 compared to air.

Alternatively argon is frequently used as tracer gas. However the signal in the mass spectrum of the residual gas has a mixed signature of mass 40 for Ar^+ and hydrocarbons and mass 20 for Ar^{++}, ^{20}Ne and $^{18}OH_2$. In addition the natural content of argon in the ambient air is significantly higher than the one of helium.

5. HELIUM LEAK DETECTORS

In principle any type of residual gas analyzer can be used as mass spectrometer helium leak detector. The most sensitive and safe device however is a mass spectrometer with 180° magnetic sector field optimized for the detection of mass 4.

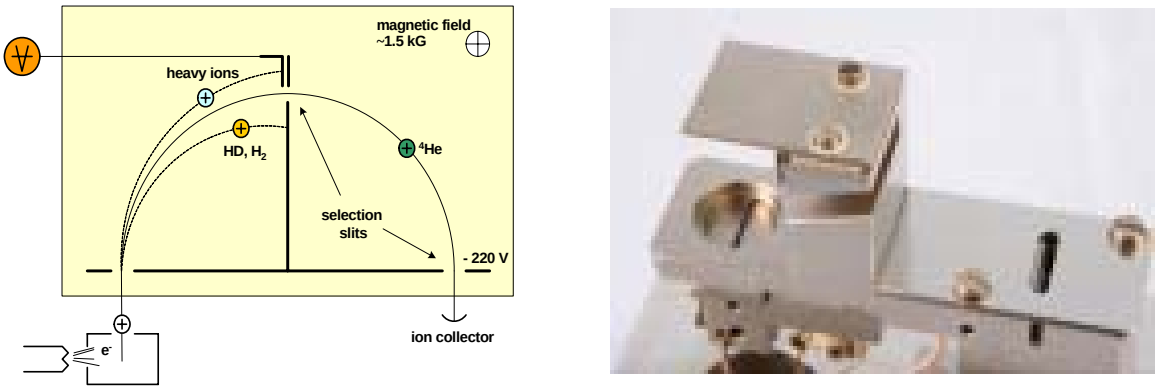

Fig. 2: Schematic drawing of a helium leak detection cell with 180° magnetic sector field (left) and photo of the slit system (right) .

Figure 2 shows a schematic drawing and a photograph of such a helium leak detection cell. The central parts are an ion source, a separation system and an ion collector system. The residual gas is ionized by bombardment with electrons. The resulting ions are accelerated into a magnetic field, where they are deflected. A system of slits allows the helium atoms to pass to a collector unit located at a deviation of 180°. All other ions are blocked. The magnetic field of about 1.5 kg Gauss is

typically produced by permanent magnets. A second collector at the middle plate is used to measure the ion current of heavy ions, which is then converted into a total pressure value.

To detect tiny leaks the currents to be measured are extremely small. At the highest sensitivity of 10^{-12} mbar·l/s currents as low as 10^{-15} A have to be measured. This is achieved thanks to the use of electron multipliers in the most modern detectors.

In a mass spectrometer the typical path length of the ions to be collected is about 15 cm. As the ions should pass without collisions with other gas molecules the operating pressure should be below 10^{-4} mbar corresponding to a mean free path of 60 cm.

6. HISTORY OF HELIUM LEAK DETECTORS

In 1910 J.J. Thomson described the first mass spectrometer used to detect Neon isotopes. For several decades such huge apparatus, easily filling a room, where operated by specialists only. The idea of using mass spectrometers for leak detection goes back to the Manhattan Project in 1942/43 [8]. The leak-tightness requirements needed for the apparatus of the uranium enrichment plants triggered the need for very sensitive and reliable leak detection systems. This led finally to the choice of a mass spectrometer tuned on the mass of helium designed by Dr. A.O. Nier [9]. The first publication dates back to 1947.

During the 50's and 60's the original choice of glass as material was replaced by a metal solution being much more robust and adequate for industrial use. Also the first compact units including a pump station – weighing about 200 kg – came onto the market. While today the leak detection cell is still very similar to the original design, the pumping systems have considerably improved replacing the original diffusion pumps by turbomolecular or even dry pumps. The sensitivity of helium leak detectors has increased from an initial value of 10^{-6} mbar·l/s by 6 orders of magnitude down to 10^{-9} mbar·l/s around 1970 and 10^{-12} mbar·l/s nowadays.

7. HELIUM LEAK DETECTION

When searching for leaks at vacuum vessels the system to be tested is continuously evacuated. The tracer gas penetrating from the outside into the system is pumped through a leak detector where its concentration is measured. For leak location the tracer gas is sprayed locally, while for total leakage measurement, the vacuum vessel is completely enclosed by the tracer gas as shown schematically in Fig. 3.

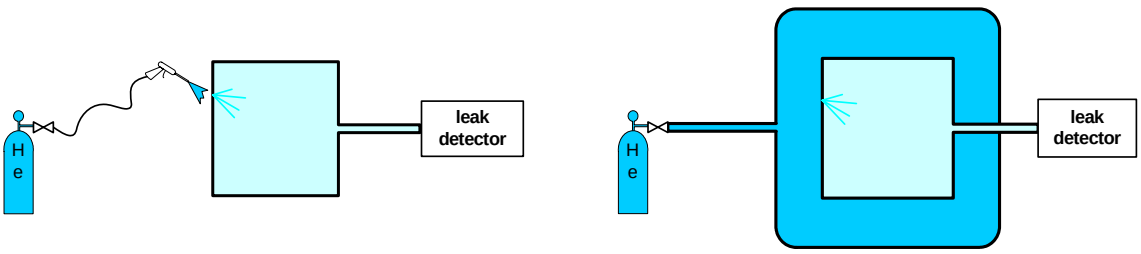

Fig. 3: Leak detection of vacuum vessels using the tracer method – left: leak location, right: total leakage measurement.

For pressurized systems the detector method is usually applied. The device to be investigated is pressurized with the tracer gas. For leak location a sniffer probe is connected to a conventional helium leak detector by a capillary tube or needle valve to reduce the pressure from atmosphere to the maximum admissible pressure of about 10^{-4} mbar (see Fig. 4, left). The detection limit of the "sniffer method" of about 10^{-7} mbar·l/s is determined by the natural He content of air. For total leakage measurement the vessel is placed into an evacuated test chamber with detector unit as shown in the right part of Fig. 4.

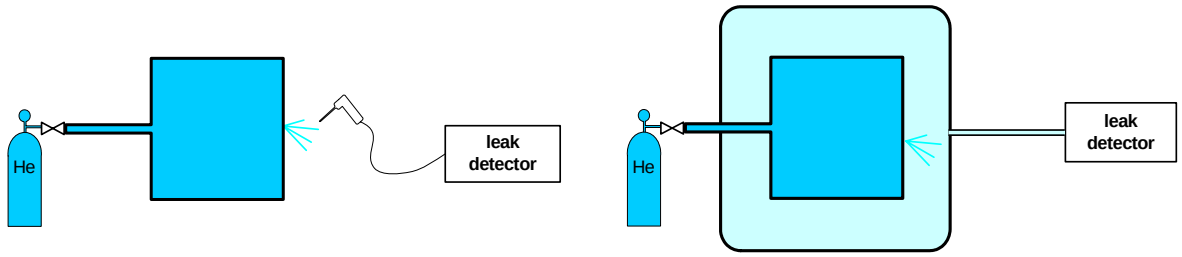

Fig. 4: Leak detection of pressure vessels using the detector method – left: leak location using a sniffer, right: total leakage measurement.

The sniffer method can also be applied in case of very large leaks of vacuum systems, when the use of any classical leak detection method is impossible as the pressure can not be sufficiently lowered. In that case the sniffer can be used to detect the presence of helium in the exhaust line of a roughing pump while spraying helium onto the system.

7.1 Direct Flow Method

In principle the leak detector can be connected to a vacuum system such that the tracer gas is flowing completely or only partially through the detection cell. Using the direct flow method, both the leak detection cell and pumps are directly connected to the vacuum system as indicated in Fig. 5. In this case the helium leak rate Q_{He} is given by the effective helium pumping speed $S_{eff,He}$ of the high vacuum pump and the helium partial pressure p_{He} within the cell:

$$Q_{He} = p_{He} \cdot S_{eff,He} \quad . \tag{2}$$

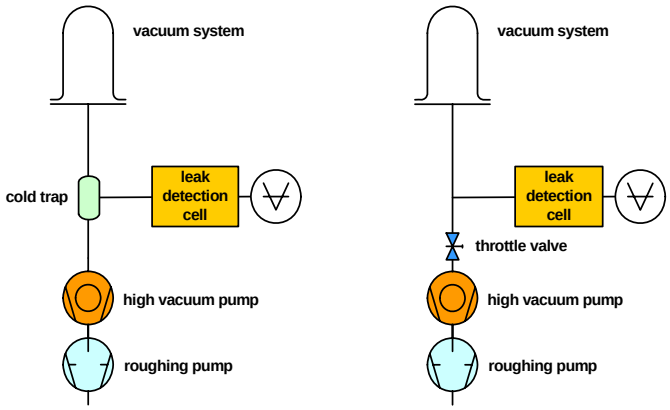

Fig. 5: Layout for the direct flow method with cold trap (left) and throttle valve (right).

The ratio between the partial pressure increase in the leak detection cell and the helium flow through the leak defines the intrinsic sensitivity of a leak detector. In order to increase the sensitivity, the pumping speed for the tracer gas has to be reduced [see Eq. (2)]. This must be done without diminishing the pumping speed for the other gases in order to keep an appropriate operating pressure for the filament emitting the ionising electrons. As leak detection usually takes place in unbaked systems, selective pumping is therefore needed to provide a high pumping speed for water and a low pumping speed for helium.

Originally diffusion pumps where most commonly used to produce high vacuum. They were combined with a liquid nitrogen trap to effectively condensate water (left part of Fig. 5). The trap also impeded back streaming of oil vapour from the diffusion pump to the leak detection cell. This arrangement has been very successful for many years, although their operation had several disadvantages. The cold trap needed to be refilled periodically during operation requiring an easy

access to a liquid nitrogen source. The diffusion pumps had to be operated in quite well defined ways as they were sensitive to misuse such as inadequate venting. Since the 80's turbomolecular pumps started to replace the diffusion pumps and cold traps.

In order to increase the sensitivity, a throttle valve could be installed as indicated in the right part of Fig. 5 to reduce the gas flow to the pumps. According to Eq. (2) decreasing the pumping speed by a factor of 10 decreases the minimum detectable leak rate by the same factor. The direct flow method is quite fast and very sensitive. Nevertheless in most commercial leak detectors it is nowadays replaced by counter-flow detectors.

7.2 Counter Flow Method

Already in 1968 W. Becker proposed a different arrangement of the pumps and leak detection cell [10]. As shown schematically in the left part of Fig. 6 the leak detection cell is no longer connected directly to the vacuum system, but to the inlet of a high vacuum pump. However the realisation of the counter flow method still took several years. Only in the middle of the 70's adequate turbomolecular pumps were available on the market [11-12].

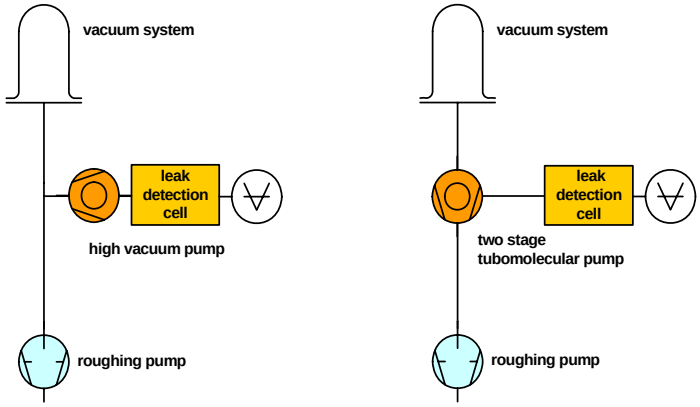

Fig. 6: Layout for the counter flow method: single stage high vacuum pump (left) and two stage turbo molecular pump (right).

The method is based on the fact that the compression ratio K of turbomolecular (and diffusion) pumps increases rapidly with the mass of the pumped gas. Hence by injecting the gas from the tested vessel at the exhaust of the pump it is possible to obtain at its inlet a backstreaming flux largely enriched for lighter gases. Typical values for the compression ratio of a turbomolecular pump running at full speed are K_{He} = 50, K_{H20} = 4000 and K_{N2} = 30.000, resulting in a suppression by a factor of 80 for water and 600 for nitrogen. Compared to the direct flow method the helium partial pressure within the detection cell is reduced by the turbomolecular pump by the factor K resulting in a leak rate Q_{He} of:

$$Q_{He} = p_{He} \cdot S_{eff,He} \cdot K \quad . \tag{3}$$

A major drawback of this simple method is the direct connection of the tested vacuum vessel to the roughing pump and thus the risk of its contamination by oil vapour. In addition, the stability of the pumping characteristics is important to ensure the necessary stability for accurate leak detection. The typically small pumping speed of the roughing pump increases significantly the time constant for leak detection.

As a remedy to the problems described above more sophisticated commercial leak detectors have been developed using specially designed turbomolecular pumps. For example installing a second turbomolecular pump between vacuum vessel and roughing pump ensures clean pumping with high pumping speed and thus a short time constant. Nowadays two stage turbomolecular pumps are most

widely used having an outlet flange between the two stages to the leak detection cell (right part of Fig. 6). Alternatively a simple counter flow leak detector can be connected to the outlet of the turbomolecular pump in a pump station. With the recent developments of dry pumps, more and more counter flow leak detectors using dry pumps are available on the market, thus avoiding contaminations from oil vapour.

The counter flow detectors offer several advantages compared to the direct flow detectors. They do not need cold traps. The tracer gas is no longer flowing directly through the detection cell, but just a part of it by backstreaming through the high vacuum pump. Hence for the same flow, the pressure in the cell is lower and consequently the detection can start earlier, i.e. at a higher pressure level of about $p \cong 10^{-1}$ mbar. In addition the leak detection cell and thus the filament are better protected in case of a sudden pressure increase. As a consequence however they are less sensitive ($1 \cdot 10^{-10}$ mbar·l/s) than direct flow detectors, the latter one being still unbeatable in the case of very small leaks.

7.3 Characteristics

Various parameters characterise a leak detector. Most important are the sensitivity, detection limit, response time and maximum allowable inlet pressure.

According to Eqs. (2) and (3) the intrinsic partial pressure sensitivity *s* for the direct flow (DF) and counter flow (CF) detector are given by the helium partial pressure and the helium pumping speed at the connecting flange of the vacuum system:

$$s_{DF} = \frac{p_{He}}{Q_{He}} = \frac{1}{S_{eff}} \tag{4}$$

and

$$s_{CF} = \frac{p_{He}}{Q_{He}} = \frac{1}{S_{eff} \cdot K_{He}} \ . \tag{5}$$

For the overall sensitivity not only the intrinsic sensitivity but also by the sensitivities of the mass spectrometer and the amplifier need to be taken into account [1].

The smallest detectable leak or detection limit is given by the ratio of the minimum detectable signal and the overall sensitivity. This means that in practice the total pressure in the detection cell needs to be taken into account. Thus using the same leak detector, the minimum detectable leak is different when testing a small vessel or a 100 m long accelerator section. The detection limit could also be limited due to a significant helium level in the atmosphere surrounding the leak detector. This could lead to a permanent high helium background signal from e.g. helium entering by permeation through O-rings, small internal leaks in the detector or via the exhaust line into the roughing pump and thus being stored in the pump oil. To counteract the latter case the roughing pump could be flushed by running with gas ballast for some period.

Another important characteristic is the time dependent behaviour of the helium signal. This is not only depending on the leak detector itself but also on the system under investigation. After spraying helium onto a vessel of volume *V* the helium partial pressure p_{He} will start to increase to its equilibrium value Q_{He}/S_{eff} according to

$$p_{He} = \frac{Q_{He}}{S_{eff}} \left(1 - e^{-\frac{t}{\tau}} \right) \ . \tag{6}$$

Here τ is the time constant

$$\tau = \frac{V}{S_{eff}} \quad . \tag{6}$$

Usually the response time is defined as the time to reach 95 % of the equilibrium value. Three examples for the time dependent behaviour of the detector signal are shown in Fig. 7. In case of curve 1 the signal reaches quickly its equilibrium value. Increasing the volume by a factor of 10 the response time will be 10 times longer (curve 2). Increasing the pumping speed will decrease the response time, but according to Eq. (2) also reduce the signal by the same factor as shown in curve 3. One has to note that the signal will start to rise after a dead time only.

When removing the test gas from the system the recovery behaviour for the three cases is similar as plotted in the right side of Fig. 7.

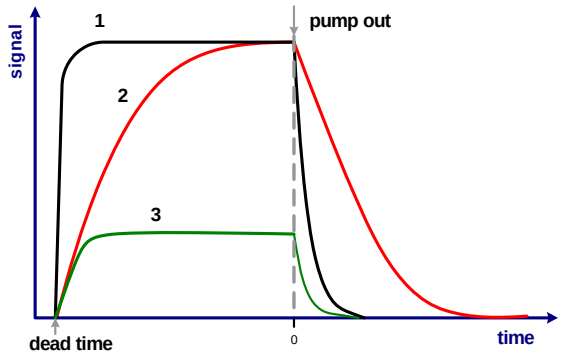

Fig. 7: Time dependent behaviour of the helium signal for a leak (left) and during pump out (right).

Before starting leak detection the system must be pumped down such that the maximum inlet pressure of the leak detector has been reached. The warm-up or start-up time defines the period needed till stable operation of the mass spectrometer is possible.

In order to perform quantitative measurements helium leak detectors need to be calibrated with a standard leak. This needs to be repeated regularly as the long-term stability usually is insufficient, especially when working on large vacuum systems. Drifts from the electronics of the detector need to be checked and eventually corrected regularly. Details of the procedures and calibration equipment may be found in Refs. [5] and [13].

8. PRACTICAL EXPERIENCE AND EXAMPLES

For practical applications the choice of a proper leak detector is important. Depending on the volume to be checked (e.g. small set-ups versus accelerator sections), vacuum level (e.g. O-ring sealed versus metal sealed systems), tolerable/expected leak rates (e.g. HV- versus UHV-systems) or frequency (mass production versus individual measurement), various leak detector systems are available on the market.

A leak search of larger systems requires systematic work. Checking the proper functioning and leak tightness of the leak detector first are mandatory. Working with reduced gas flow from helium bottles, the system should be searched from top to bottom and against an existing air flow when working e.g. in a tunnel. One should also keep in mind that small leaks might initially be blocked by water and only open up after sufficient pumping time or even after bake-out. This may require several leak checks at various vacuum levels.

Recording the pressure and other relevant parameters during pump down and operation of a vacuum system can save a lot of time to analyse and diagnose the behaviour of the system. Any deviation from the usual pump-down curve is a hint for a possible leak. If the system is pumped for

the first time, more experience is necessary to evaluate the pressure curve. As indicated in Fig. 8 the pressure of a tight system is decreasing linearly with time in a log-log scale, while in the presence of a leak the pressure tends to level off at a value given by ratio of the leak flow to the pumping speed [7]. Similar information can be taken from the pressure increase versus time in case of isolating the vacuum system from the pumps as described in more detail in subsection 4.2 and shown in Fig. 1.

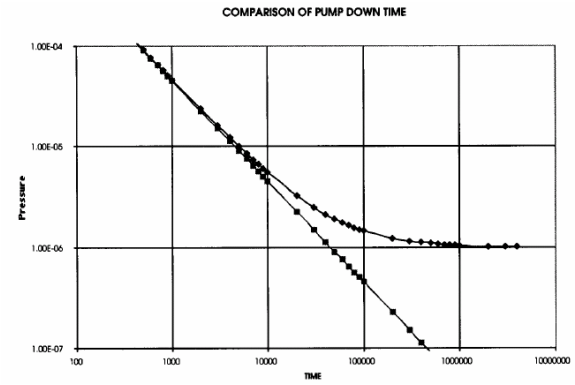

Fig. 8: Pressure versus time during pump-down with and without a leak [7].

As it is much faster and easier to find and repair leaks in a laboratory than in an accelerator, a careful check of all components prior to installation is strongly recommended. This should include the usage of metallic gaskets on all sealing surfaces.

8.1 Virtual Leaks

A virtual leak looks like a real leak in a pump-down or pressure rise curve. However there will be no signal in a leak detector and it cannot be located from outside. Usual causes for such leaks are a poor design and/or poor manufacturing of the vacuum vessel, e.g. excavations, dead holes for screws, air enclosures in a weld or narrow slits leading to excessive outgassing. Diagnosis could be done using a residual gas analyser and measuring the gas composition before and after venting with argon. After such a venting, the argon replaces the nitrogen in the virtual leak leading to an Ar enhancement in the residual gas after the second evacuation.

8.2 Cold Leaks

When operating a vacuum system at extreme temperatures (hot or cold) additional leaks could open up. A typical arrangement for testing a vacuum vessel, e.g. a superconducting cavity at temperatures below 4.5 K is shown in Fig. 9. The vessel is immersed into liquid helium, while generally pumps, vacuum gauges, leak detector and residual gas analyser are operated at the room temperature part of the system. In the presence of a “cold leak” He atoms will directly enter from the liquid into the vacuum vessel and at least be partially absorbed onto the cold walls. Thus the delay between the atoms entering the system and a significant He signal in the detectors might be very long. In practise such systems are warmed up to about 10 K after a certain time period to release the He atoms from the walls for measuring the total leak rate. Leak location requires the system to be warmed up to room temperature; however it’s not exceptional that cold leaks close reversibly and/or are not detectable after warm up.

Alternatively hot extractor gauges can be operated at liquid helium temperatures as indicated in Fig. 9. As these gauges are very sensitive to helium they can be used for in-situ leak detection as described in more detail in Ref. [14].

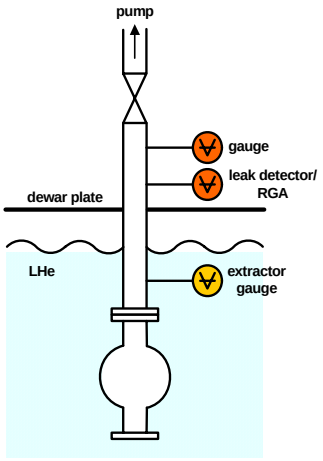

Fig. 9: Set-up for testing a superconducting cavity in liquid helium (LHe) at temperatures below 4.5 K.

8.3 Total Leakage Measurement

As described in section 7 for total leakage measurement the vacuum vessel is completely enclosed by a tracer gas. Leaving the system without active pumping and thus accumulating the tracer gas very small leaks can be detected, especially on big volumes. For example in the HERA proton ring large parts of the beam pipe are surrounded by liquid helium from the superconducting magnets. The integral leak rate of a section of about 1.4 km was determined by looking for helium during a warm-up of the beam pipe after a longer period at liquid helium temperature. Using a residual gas analyser no helium signal could be detected resulting in a total leak rate below 10^{-15} mbar·l/s at 4.5 K [15].

Examples for total leakage measurements of pressurized systems are given elsewhere in these proceedings [16].

9. HE LEAK DETECTORS - STATE OF THE ART

Today's commercial leak detectors offer a wide variety of products. Very compact and even portable units are available. Triggered by semiconductor industry an increasing number of oil free leak detectors are on the market.

Standard detectors use the counter flow method. A flexible system of valves allows injecting the helium flow into the detection cell from various locations of the pumping system, thus giving a huge range of sensitivity from quite large to very small leaks. The lowest quoted values for the minimum detectable leak are $5 \cdot 10^{-12}$ mbar·l/s respectively $5 \cdot 10^{-8}$ mbar·l/s for sniffers. The mass selection system is optimized for ^{4}He as the standard tracer gas, mostly including the option to use masses 2 (H_2) and 3 (^{3}He).

The electronics usually is equipped with semiconductors and thus sensitive to radiation. For applications requiring radiation hard solution old fashioned tubes are still without alternatives. Typical start-up times are in the order of a few min, response times less than 1 s. A high degree of automation is standard, usually including calibration, tuning and regular correction of the zero line.

10. CONCLUDING REMARK

Accelerator vacuum systems do have demanding requirements for leak tightness. Proving that the leak tightness specifications are fulfilled as well as detection and location of leaks require adequate leak detection methods, appropriate leak detectors and well trained personnel. The various methods presented during this lecture are well suited to measure and localize the full range from very large to tiny leaks. A variety of suitable commercial leak detectors are available on the market. There has been

great progress in operational availability, performance and size since 1950, when the first devices came onto the market. During the past 20 years improvements were mainly in handling and automation. Today's leak detection equipment is robust, easy to use and offering a large range of sensitivity. Nevertheless finding and repairing leaks is a time consuming process, especially in case of emergency leak testing of a running accelerator system. It still requires well trained and experienced technicians with good knowledge of the system to be checked. Therefore most important is to prevent leaks during all stages of design, manufacturing and assembly.

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