LEAK DETECTION

N. Hilleret
CERN, Geneva, Switzerland

Abstract
Various methods used for leak detection are described as well as the instruments available for this purpose. Special emphasis is placed on the techniques used for particle accelerators.

1. INTRODUCTION

Leak detection is a very important step in the production of vacuum. It is needed after the production of a vacuum vessel to check that the tightness specifications are fulfilled, during and after the assembly of these vessels to locate the possible leaks created during assembly, and finally during the installation of the vessel, to guarantee that the process can be carried out under the required pressure and gas composition conditions. Hence methods of ever-increasing sensitivities have been developed to follow the ever more stringent requirements of the industry. After a summary of the various methods used to locate leaks, the most widely used leak detector will be presented with its different types. Some practical cases will then be reviewed in the context of accelerator operation.

2. METHODS

Depending on their size, leaks can have various effects, which can be used for their location. All methods are based on the variation of a physical property measured on one side of the vacuum vessel wall while the pressure or the nature of the gas is changed on the other side. Big leaks, involving large gas flow can generate mechanical effects, smaller leaks require finer methods. These rely on the change of the residual gas physical properties when the nature of the gas leaking into the system (tracer gas) is changed. Both categories will be reviewed hereafter. A list of the possible leak detection methods with their sensitivities can be found in Ref. [1]. A comprehensive review of the methods and apparatus for leak detection can be found in Refs. [2, 3].

2.1 Mechanical effects

As explained above the production of measurable mechanical effects requires a sufficient energy and hence these methods are limited to relatively large leaks. The emission of sound or the deflection of a flame can occur in the case of leaks (10^{-2} to 10^{-3} $Pa.m^3.s^{-1}$), usually limiting the pressure in the rough vacuum domain. Ultra-sound detectors can also be used to monitor the oscillations produced by the gas in the vicinity of leaks. A more sensitive method is the formation of bubbles when water is spread on the leak, the vacuum vessel being pressurised to several bars of over pressure. The detection limit in that case can reach 10^{-5} $Pa.m^3.s^{-1}$ if a wetting agent is added to water and it is good practice to pressurise the vessel before immersing it in the liquid as the molecules might be unable, despite the gas pressure, to flow through the surface film because of the surface tension of the liquid. These methods have the advantages to be simple, very quick to carry out, and able to locate leaks. Their sensitivity and time constant are independent of the volume of the vessel. They apply mainly to the high-pressure region.

2.2 Tracer gas

In the case of small leaks, the energy of the gas flow is insufficient to generate measurable mechanical effects. In that case a greater sensitivity is obtained by relying on the variation of physical properties of the residual gas for which accurate and sensitive measurement methods are available. When the composition of the residual gas is modified by the injection in the vicinity of the leak, of a gas (the tracer gas) changing locally the air composition, these properties are altered and this

alteration can be measured for determining the size and the position of a leak. The tracer gas must have the following properties [4], for the case of helium leak detection:

Be unique in the mass spectrum of the residual gas in the system and practically non-existent in the normal surrounding atmosphere.

Be readily removable from the system by pumping and should not contaminate the systems

Have a low viscosity.

Many properties of the residual gas can be used to monitor its composition changes. The most widely used are the heat conductivity, the ionisation cross section, the pumping speed and the conductance. The variation of heat conductivity is traced using a Pirani gauge and using alcohol, helium or carbon dioxide. The pressure variation on the gauge will be positive for helium and negative for alcohol or carbon dioxide. The variation in ionisation cross section can be used by monitoring the signal of an ionisation gauge and this method, very useful in accelerators, will be described in the Section 4.3. Lastly, the mass of the molecules can also be used to trace leaks and this very sensitive and widespread method is described in the next section.

3. HELIUM LEAK DETECTORS

3.1 History and principle

At the origin of the helium leak detection method was the ”Manhattan Project” and the unprecedented leak-tightness requirements needed by the uranium enrichment plants. The required sensitivity needed for the leak checking led to the choice of a mass spectrometer designed by Dr. A.O.C. Nier [5] tuned on the helium mass (see the tracer gas definition above). Because of its industrial use, the material choice (originally glass) turned out to be unbearably fragile and after many complaints by the users, a new metallic version was developed and constructed. The sensitivity of the apparatus was in 1946 ~10^{-7} Pa. $m^3.s^{-1}$ and it increased to ~10^{-10} Pa. $m^3.s^{-1.}$ by 1970. Nowadays the quoted sensitivity of the most sensitive detectors is ~10^{-13} Pa $.m^3.s^{-1}$, a factor 10^6 gain within 50 years.

The central piece of the helium leak detector is the cell in which the residual gas is ionised and the resulting ions accelerated and filtered in a mass spectrometer. Most of the current detectors use, as in the original design, a magnetic sector to separate the helium ions from the other gases. Permanent magnets are generally used to generate the magnetic field. The adjustment needed for the selection of the helium peak is made by varying the ion energy. A schematic layout of a helium leak detection cell is given in Fig. 1.

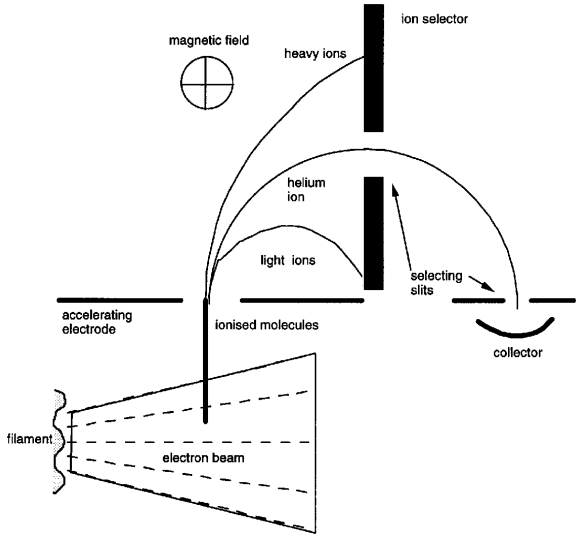

Fig. 1 Schematic layout of a leak detection cell.

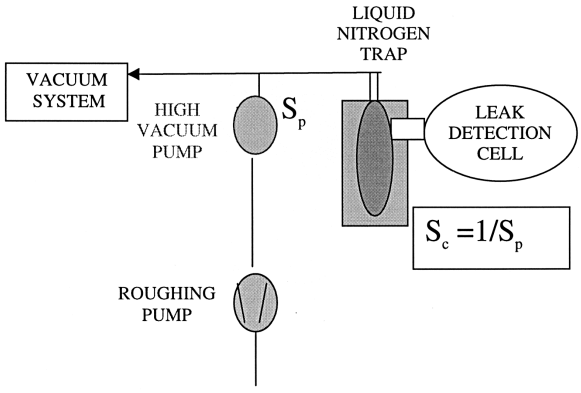

Fig. 2 The direct-flow layout.

To detect small leaks, the currents to be measured are very small: At the highest sensitivity (in the 10^{-13} Pa .$m^{3.}$.s^{-1} range), currents as low as femtoamperes have to be measured. This is achieved thanks to the use of an electron multiplier in the most modern detectors. If the cell of a leak detector is not much different from the original design, the pumping system has considerably changed, the original diffusion pumps now being replaced by turbomolecular pumps or dry molecular-drag pumps.

The sensitivity of the helium leak detector is given by the ratio between the helium flow through the leak and the partial pressure increase in the cell. In order to increase the sensitivity, the pumping speed of the tracer gas has to be reduced. This must be done without diminishing the pumping speed for the other gases (mainly water as leak detection usually takes place in unbaked systems) in order to keep the appropriate operating pressure for the filament emitting the ionising electrons. Selective pumping is therefore needed to provide a high pumping speed for water and a low pumping speed for helium. The various ways to achieve this will be presented in the next Section.

3.2 The direct-flow method

In direct-flow leak detectors, the vacuum system is connected according to Fig. 2 to the leak detection cell and to its pump.

To provide selectivity, a liquid-nitrogen trap is installed between the leak detection cell and the input flange of the detector. The high pumping speed of the trap for water allows the pressure in the cell to be lowered and, hence, leak detection to be started earlier without losing helium sensitivity. This arrangement has been very successful and such detectors were able, on small systems, to detect leaks as low as 10^{-12} Pa.m^3.s^{-1}. They used diffusion pumps and were sensitive to misuse such as inadequate venting leading to the oxidation of the diffusion-pump oil. Furthermore when the detector was operating, the nitrogen trap needed to be refilled periodically: an easily accessible source of liquid nitrogen was required. This trap also impeded the diffusion-pump oil-vapor to backstream to the cell. This is very important to avoid the deposition in the cell container of insulating coatings formed during the interaction of the ionising electron beam with the oil vapors. Lastly, because of the warming up time of the diffusion pump, their start-up required approximately 15 minutes and the sequence to operate them was complicated. On the other hand, the tested vacuum system was exposed to the residual gas of a trapped diffusion pump, which in these time was the most common pumping system to produce high vacuum. These detectors were used for most of the leak checks in high vacuum systems until the mid 80's. Nowadays they are being replaced by counter-flow detectors

3.3 The counter-flow method

The possibility of using this method for leak detection was mentioned by W. Becker in 1968 [6] and later described elsewhere [7, 8]. Since then this method has become widely adopted in the field of helium leak detection.

The method is based on the fact that the compression ratio of turbomolecular pumps and diffusion pumps increases very quickly with the mass of the pumped gas. Hence it is possible by injecting the gas from the tested vessel at the exhaust of the pump to obtain at its inlet a backstreaming flux largely enriched in lighter gases. For example, for a turbomolecular pump running at full speed the ratio between the compression ratio for helium and water vapor is 10^4. A scheme of such a leak detector is given in Fig. 3. Although the scheme was initially proposed both for diffusion pumps and turbomolecular pumps, most of the existing counter-flow detectors use turbomolecular pumps.

A major drawback of this simple scheme is that the tested vessel is connected directly to the forepump and can be contaminated by oil vapor. Furthermore, the stability of the pumping characteristics of the forepump are very important to ensure the stability needed for accurate leak detection. Lastly the pumping speed of the forepumps used for such application is small and the time constant for the leak detection is hence greatly increased.

To remedy these problems more sophisticated commercial leak detectors have been developed using specially designed turbomolecular pumps. The vacuum system is pumped by a first turbomolecular pump ensuring clean pumping with a high pumping speed and correspondingly short time constant. A second integrated turbomolecular pump, having a common outlet flange, is connected to the leak detection cell, Fig. 4. These advantages are also obtained by using a simple counter-flow leak detector connected to the outlet of the turbomolecular pump in a roughing station (see Fig. 5 in the chapter on mechanical pumps in these proceedings). A similar configuration can be obtained by admitting the gas at various intermediate stages of a turbomolecular pump. Depending on the size of the leak, or on the total gas flux to be evacuated, the gas can be injected in the high-pressure stages ("gross" leak configuration) or closer to the low-pressure stages for an enhanced sensitivity.

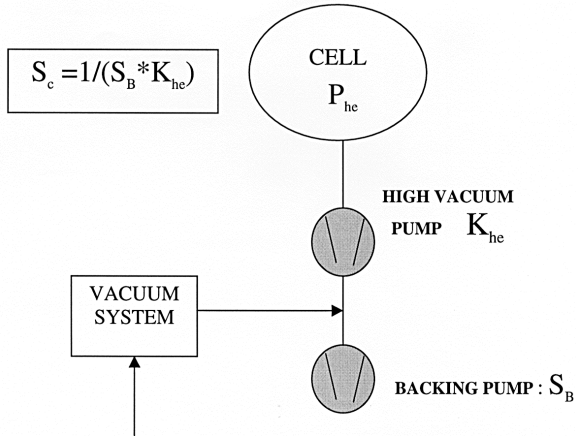

Fig. 3 Counter-flow leak detection method

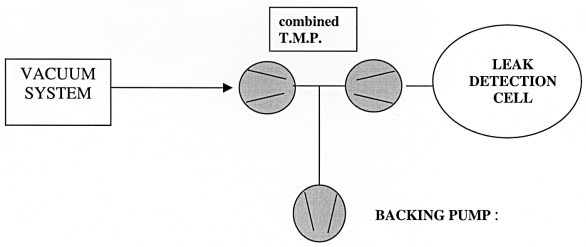

Fig. 4 Combined turbo-molecular-pump leak detector

With the development of dry pumps, new counter-flow detectors have been built using dry pumping systems to avoid contamination by the oil vapor coming from the detector pumps. Another interesting improvement is the introduction of molecular-drag pumps in place of the high-pressure stages of the turbomolecular pump. Because of the high pressure tolerable at the outlet of such pumps, leak detection is made possible with a much higher pressure in the system, thus providing the possibility of an early detection (i.e. a high pumped flow).

The advantages of counter-flow detectors are numerous: they do not need liquid nitrogen, they can be easily transported, they are more quickly put into operation, because of the inertia of the pump rotor, the filament is more protected in case of a sudden air inrush. In general they are more robust and require less maintenance, their simple mode of operation also permits easier automation and remote control. Most of the recent leak detectors use the counter-flow method. Nevertheless the direct-flow geometry offers for the case of very small leaks ($< 10^{-12}$ $Pa.m^3.s^{-1}$) a better stability of the signal and hence an up-to-now unsurpassed sensitivity.

3.4 The detector probe method (sniffer)

This method is very similar to the two preceding ones as it uses the same apparatus: a helium leak detector. In the case of the "sniffing method", the vessel itself is pressurised with the tracer gas (usually helium). Then the gas outside the vessel is tested to detect the presence of the tracer gas. This testing is made by admitting, through a needle valve or a capillary tube, the gas in a conventional helium leak detector (either direct or counter-flow) at its maximum admissible pressure. This method is very useful for locating large leaks in vessels contaminated by, or containing, helium. The detection limit of the method is close to 1×10^{-1} $Pa.m^3.s^{-1}$.

This method can also be used in the case of very large leaks impeding, because of the impossibility to lower sufficiently the pressure, the use of any classical method of leak detection. In that case the "sniffer" is used to detect the presence of helium in the exhaust gas of a roughing pump while spraying helium on the leaking system.

3.5 Characteristics of leak detectors

To specify helium leak detectors it is important to define several characteristics. The sensitivity of the helium leak detector is often confused with the smallest detectable leak. The intrinsic sensitivity *s* is defined as the ratio between the leakage flow Q_l and the helium partial pressure P_{He} in the leak detector cell:

$$S = \frac{Q_l}{P_{He}}$$

In the case of a direct-flow leak detector, with a cell pumping speed S_{He} the sensitivity *S* is:

$$S = \frac{1}{S_{He}}$$

In the case of a counter-flow leak detector, the sensitivity is:

$$S = \frac{1}{S_b \times K_{He}}$$

with S_b the pumping speed of the backing pump for helium and K_{He} the compression of the turbomolecular pump for helium. This sensitivity is a characteristic given by the construction of the detector, its pumping speed and compression.

The smallest detectable leak that is an important characteristic from the operational point of view is defined as the minimum detectable leak signal. It is given by the intrinsic sensitivity of the leak detector and the peak-to-peak noise of the leak signal. This noise depends on the total pressure in the cell and hence on the operating conditions. The minimum detectable leak is different when the detector is connected to a small vessel or to a 100-m long accelerator sector. To avoid any confusion the exact operating conditions for the measurement of the minimum detectable leak must be defined in the specification.

Another characteristic of interest is the long-term drift of the detector. This characteristic is especially important in the leak detection of large systems with long time constants and defines the stability in percent of the signal over a given time period.

For various reasons, the leak detectors sometimes receive large flows of helium. It is important to measure the time needed by the leak detector after such an incident to recover a low helium signal. Of course this measurement must be done on an isolated detector to eliminate the time constant introduced by the vacuum system itself. Another possible reason for a high helium background signal is the presence in the atmosphere surrounding the leak detector of a high helium concentration. This can happen in halls where large quantities of liquid helium are handled with unavoidable losses. In that case helium can penetrate the leak detector circuits by permeation through elastomer gaskets or through small internal leaks in the detector. This also causes a high background signal and must be specified and tested.

The highest operating pressure of the leak detector largely determines the speed of an intervention in an accelerator. As a matter of fact, if leak detection can be carried out with an acceptable sensitivity at pressures in excess of 10 Pa, the waiting time before starting leak detection is determined by the removal of the gas contained in the vessel. At a pressure lower than 10 Pa, the degassing of the walls plays an increasing part. In that case the pressure decay in the leak detection cell i.e. the decay of the total flow, is inversely proportional to time and cannot be influenced without increasing the value of the minimum detectable leak. On the contrary, if the operating pressure is greater than 10 Pa, larger auxiliary pumps can be used to decrease the time needed to reach the detection threshold and can be valved off during the leak detection. For these reasons, the operating pressure of the leak detector is of great importance for quick interventions in an accelerator.

The procedures and equipment to calibrate a helium leak detector are described in the Ref. [9].

4. PRACTICAL CASES

4.1 Early detection of leaks

During the operation of a vacuum system much time can be saved by logging all the relevant information concerning the pressure decay during a roughing cycle. Any deviation from the usual pump-down curve is the sign of a possible leak. If the system is pumped for the first time, the shape of the pump down curve can also indicate the possibility of a leak: in Fig. 5 the typical pressure decay of a tight and a leaky system are shown. For pressures lower than 1Pa, the normal water degassing which constitutes the main constituent of an unbaked system is inversely proportional to time (-1 slope of the pressure-versus-time curve on a log-log scale). If a leak is present in the system, the pressure will tend to a limiting pressure given by the ratio of the leak flow to the pumping speed. A similar observation can be made by isolating the vacuum system and measuring the pressure increase as a function of time. Figure 6 shows three typical curves of pressure versus time on a linear scale: a linear behaviour is an indication of a leak. The initial part of the measurement should not be considered as the normal degassing of the system is predominant in that part of the curve.

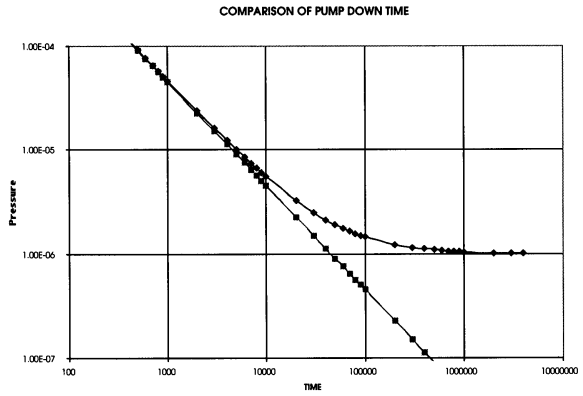

Fig. 5 Various pump-down curves

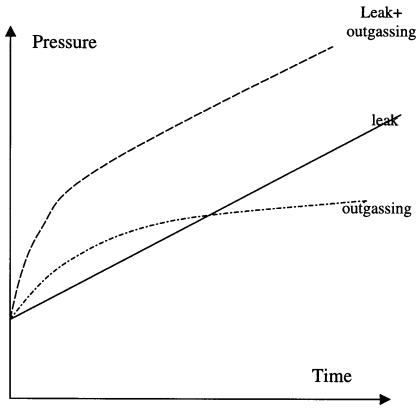

Fig. 6 Comparison of pressure increase in the presence of a leak or of degassing

If a gas analyser is present in the system, valuable information can be drawn from the residual-gas composition. On many occasions it has been observed that the presence of a peak at mass 14 (nitrogen) higher than the peaks at mass 12 or 15 (carbon and CH_3) after 24-hours pumping is, in an all-metal unbaked system, an indication of the possible presence of a leak. In a baked system, the mass 28 (nitrogen and carbon monoxide) is difficult to use as carbon monoxide is an important peak in baked systems. Argon (mass 40) and oxygen (mass 32) are more useful indicators of the presence of a leak although oxygen is not always visible on the mass spectrum as the pumping speed of baked stainless steel for this gas is high.

4.2 The use of leak detectors

In an accelerator, leak detection can be carried out in various ways: It is good practice to make an individual leak detection of all components before installing them in an accelerator since a leak is much easier to find and to repair in the laboratory than in the accelerator tunnel. This also has the advantage of reducing leak testing in the tunnel and hence the radiation dose received by the installation personnel. The leak tests can be made either by holding bags filled with helium around the mounted joints, or by blowing helium around the points to be tested. Both procedure have their advocates, the first one being longer but more systematic, the second one being faster and allowing the leaks to be located directly. In both cases, the time constant of the vacuum system must be carefully evaluated in order to spend, at each location, the time necessary for the helium signal to increase significantly. The evolution with time t of the helium signal P, for a system of volume V pumped with a pumping speed S and having a leak Q is given by (taking the initial pressure of tracer gas as zero):

$$P = \frac{Q}{S} \times \left(1 - e^{-St/V}\right)$$

Sixty three per cent of the full leak signal is obtained after 100 seconds if a 100-litre volume is evacuated with a 1-litre-per-second pump.

The helium leak detector is a complicated and sometime delicate instrument. It can loose partly or totally its sensitivity and hence it is of utmost importance to periodically check and readjust the sensitivity of these instruments. This is achieved by using calibrated helium leaks delivering to the instrument a known helium flow and adjusting the instrument settings (very often the ion accelerating voltage) for the maximum signal. Then, tuning the emission current sets the absolute value of the sensitivity. In most of the modern instruments, this calibration is made automatically at the start-up of the detector.

The presence of air movements is very important as they can transport the tracer gas and induce a wrong interpretation of the position of a leak. For this reason it is necessary to notice the direction of a possible air flow and to start the leak detection upstream.

4.3 Leak detection using total pressure gauges

This method is extremely useful in large accelerators, especially in the case of baked machines where the connection of a helium leak detector is a lengthy procedure. It is described for the case of the ISR at CERN in Ref. [10]. The method is based on the variation of the pumping speed, the gauge sensitivity and the conductance of the gas entering the leak. Because of the change of these factors, the ion current collected by an ionisation gauge is modified when the nature of the gas leaking in the system changes. The sensitivity of this method depends greatly on the configuration of the vacuum system, the types of gauges and pumps. In the forthcoming calculation, two extreme cases will be considered depending on the gauge location with respect to the pumping station: either at the pumping station or far from it. The geometry of the system studied for this example is shown in Fig. 7, the case of Bayard Alpert gauges is considered.

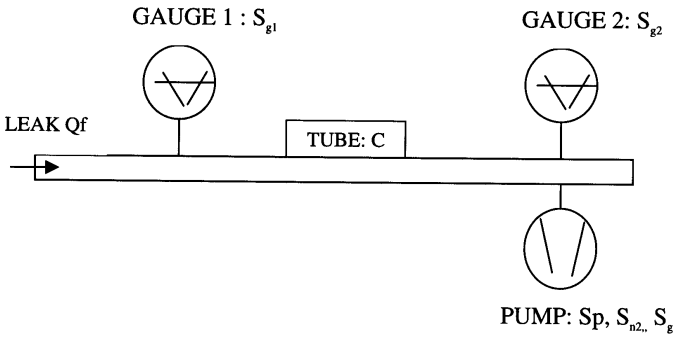

Fig. 7 Leak detection with pressure gauges

At the leak and in the accelerator tube, the ratio of the flow (in the molecular regime) for the tracer gas Q_g and the air Q_{air} is equal to the ratio of the conductance of the tube for these two gases:

$$\frac{Q_g}{Q_{air}} = \sqrt{\frac{29}{m_g}} = \frac{C_g}{C_{air}}$$

where the subscripts *g* and *air* refer respectively to the tracer gas and the air.

For the gauge 1, far from the pump, the pumping speed S_{g1} is equal to the conductance *c* of the pipe.

For the gauge 2, at the pump, the pumping speed S_{g2}.

At the sensors the pressure P_{sg} is

$$P_g = \frac{Q_g}{S_g} \ .$$

The corresponding current on the collector gauge I_g is:

$$i_g = i_e \times s_g \times P_g = i_e \times s_g \times \frac{Q_g}{S_g}$$

where i_e is the emission current of the gauge. When changing from air to the tracer gas, the variation in collector current is (valid for the gauge 2):

$$\frac{i_g}{i_{air}} = \frac{s_g}{s_{air}} \times \frac{Q_g}{Q_{air}} \times \frac{S_{air}}{S_g} \ .$$

For the gauge 1 located far from the pump: $S = C$ hence:

$$\frac{i_g}{i_{air}} = \frac{s_g}{s_{air}} \times \frac{Q_g}{Q_{air}} \times \frac{C_{air}}{C_g} = \frac{s_g}{s_{air}} \ .$$

When changing from air to the tracer gas the ratio of the gauge readings is the ratio of the sensitivity of the gauge for nitrogen and tracer gas.

Let us consider the case of two tracer gases, helium and argon, and two types of pump, a sputter ion pump and a combination of sputter-ion pump and sublimation pump. The relevant numerical values are for the pumps and gauges in use at CERN are given in Table 1. Applied to the above equations these values give the ratios given in Table 2 for the variation of the gauge current when air is replaced by the tracer gas.

Table 1
Values of pumping speed and gauge sensitivity for different gases

Gas	Gauge sensitivity (relative to nitrogen)	Pumping speed of ion pump	Pumping speed of ion + sub. pump
Air	1.2	400	1400
Helium	0.15	100	100
Argon	1.4	100	100

Table 2
Variation ratio of the gauge reading when air is replaced by helium or argon

Gas	Gauge far from pump	Gauge at ion pump	Gauge at ion + sub. pump
Helium	0.18	2.4	8.4
Argon	1.7	5.6	20

These numbers show that depending on the position of the gauge with respect to the pump, and of the type of pumping, variations can be expected on the gauge current when air is replaced by a noble gas. The effect is especially large when the pumping relies on the chemisorption since noble gases are not pumped by this mechanism. Gauges located at the pump also show a greater effect. Argon gives an amplification of the signal under all circumstances and for this reason is preferable to helium. In the case of accelerators pumped by getter pumps, this method is especially well suited. A reactivation of the getter, or a sublimation just before detection, can greatly increase the sensitivity of the method.

4.4 Virtual leaks

This type of leak appears, on the pumping curve, as a real leak but cannot be located from outside. It is due to internal defects causing the retention of gas in a poorly-pumped pocket. Usual causes for

such leaks are poor design and/or poor manufacturing of the vacuum vessel. They are of course invisible by a leak detector but can be revealed by connecting a residual-gas analyser and checking the composition before and after venting with argon. After such a venting, the argon replaces the nitrogen in the virtual leak and an abnormally high argon content is present in the residual gas after the second evacuation.

4.5 The accumulation method

For the detection of very small leaks, an important gain can be made by leaving the unpumped system exposed to the tracer gas. This gas accumulates in the system and its concentration can be measured periodically either with a residual-gas analyser or with a helium leak detector if helium is used. Leak rates lower than 1×10^{-12} $Pa.m^3.s^{-1}$ are measurable with this method on big volumes. For example a 1×10^{-8} Pa partial pressure variation over a period of 48 hours in a vessel of 10 m^3 is produced by a leak of 8×10^{-13} $Pa.m^3.s^{-1}$. It is possible to apply this method using air as tracer gas by checking the argon peak increase in the vessel provided that the argon degassing by welds can be neglected.

5. CONCLUSION

The various methods that can be used for the leak detection of accelerator systems cover the large range of possible leaks from the broken feedthrough to the tiny leaks appearing after bakeout. The vacuum specialist now has at his disposal efficient tools allying robustness with sensitivity and ease of use. Thanks to the development of molecular-drag pumps, the availability of leak detectors able to detect leaks at pressures in excess of 10 Pa is a great advantage in reducing the down-time of accelerators during emergency interventions. Despite the quality of the equipment now commercially available, leak detection remains an exercise, which, generally, is still difficult and requires well-trained technicians with a good knowledge of the vacuum system on which they intervene. Even with the best technicians using the most sophisticated equipment, emergency leak testing is always a time consuming and very expensive activity. For these reasons careful mechanical design and construction according to the rules of good vacuum practice must be applied. Preliminary tests of components must be made before installation: they are always much easier to carry out and avoid the costly installation and demounting of faulty equipment. Lastly these somewhat theoretical considerations on leak detection are a minute part of all the knowledge required to become “a subtle leak hunter” and which is only accessible “the hard way” by practice.

ACKNOWLEDGMENTS

I would like to thank my technical colleagues at CERN for their skill in teaching me the art of leak detection.

REFERENCES

[1] A. Roth, Vacuum Technology, New York, Elsevier Science Publishers, 1990.

[2] J.F. O'Hanlon, A Users Guide to Vacuum Technology, New York, John Wiley & Sons, 1989.

[3] J.M. Lafferty, Foundations of Vacuum Science and Technology, New York, John Wiley & Sons, 1998.

[4] A. Nerken, J. Vac. Sci. Technol., A9, 3, 2036, 1991.

[5] A.O. Nier, C.M. Stevens, A. Hustrulid and T.A. Abott, J. Appl. Phys. 18, 30, 1947.

[6] W. Becker, Vak. Tech., 8, 203, 1968.

[7] M.H. Hablanaian and W.E. Briggs, Proc. Int. Vac., Congr. 7th, Vienna, 199, 1977.

[8] M.H. Hablanaian and W.K. Huber, Proc. Int. Vac., Congr. 7th, Vienna, 199, 1977.

[9] International Standards Organisation, 1 rue de Varembé, CP56, CH1211 Geneva 20, Switzerland, http://www.iso.ch ISO3530:1979.

[10] C. Benvenuti and J.C. Decroux, Le Vide, 162, 243, 1972.