

PRESSURE MEASUREMENT WITH IONIZATION GAUGES

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Abstract

A brief history, the design, the use, and the calibration of ionisation gauges are described in this article.

1. INTRODUCTION

The pressure p in an enclosed gaseous system is defined as the force dF per area dA exerted by the gas in the chamber. In a fundamental manner, forces can be measured for practical areas of a few square centimetres down to about 1 Pa, for example with elaborated U-tube manometers, filled with mercury or oil. In capacitance diaphragm gauges or membrane gauges the force is used to bend a membrane due to a differential pressure, but the force cannot be determined in a fundamental way and the gauge has to be calibrated. In the high and ultrahigh vacuum regime, however, it is no more possible to use the force on a certain area as indicator for pressure and other physical properties of the gas like gas friction, viscosity, thermal conductivity, or particle density are used to indicate pressure.

In ionisation gauges (IG) the particle density n in their gauge volume is measured. Therefore it is important to remember the ideal gas law for an enclosed system in equilibrium

$$p = nkT. \quad (1)$$

It is not sufficient to measure n with an ion gauge, but also the temperature T of the gas has to be known to indicate pressure with an IG.

How is n measured with an IG? As the name implicates, neutral gas molecules are ionised and then counted, usually by measuring a current. The ionisation normally takes place by electrons, but also photons (high intensity lasers) or ions can be used (Fig. 1).

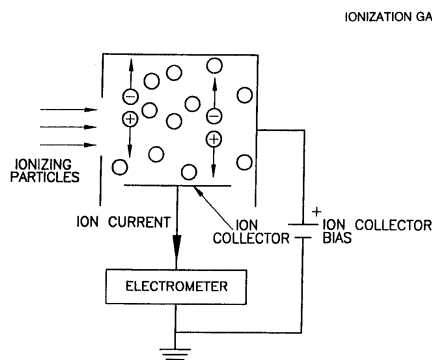


Fig. 1 The basic measuring principle of ionisation gauges. From James M. Lafferty, *Foundations of Vacuum Science and Technology*, John Wiley & Sons, New York, 1998.

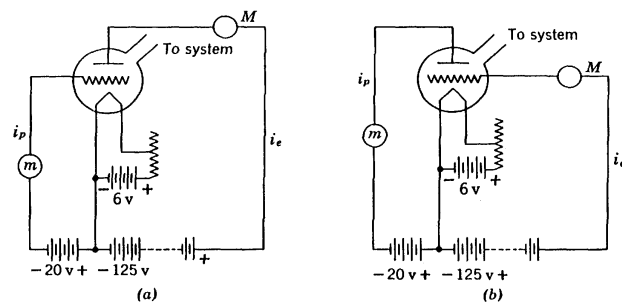


Fig. 2 Electrical circuits for triode ionisation gauges: (a) Internal control type. (b) External control type. From Saul Dushman, James M. Lafferty, *Scientific Foundations of Vacuum Technique*, 2nd edition, John Wiley & Sons, 1962.

2. BRIEF HISTORICAL REVIEW

The history of the IG dates back to 1909, when Baeyer showed that a triode vacuum tube could be used as a vacuum gauge. As inventor of the triode gauge, however, is usually named Buckley in 1916, who later improved the gauge to a lowest pressure measurement limit of about 10^{-6} Pa.

Three electrodes, sealed in a glass bulb, were needed for an IG: The cathode, as the source of electrons, the anode, and the collector of positive ions (Fig. 2). It was possible to use the grid as ion collector as shown in Fig. 2 (a), but to use the anode plate as collector (b) was customary because it was more sensitive. More ions were collected.

A few basic ideas shown in Fig. 2 are identical in today's gauges. That is, the ion collector has to be negative with respect to the cathode, so as to pick only ions and no electrons, and the acceleration voltage for the electrons has to be roughly 100 Volt. The reason is that the ionisation probability of a neutral gas molecule by an electron is energy dependent, and close to 100 eV there is a maximum for most gases as can be seen in Fig. 3.

Because the electron energy should be high on a their total path length, the acceleration voltage is usually tuned somewhat higher than 100 V. This has also the advantage that the ionisation cross-section differences between different gases are less emphasised.

The basic design of the triode gauge remained unchanged for more than 30 years, although the physicists wondered why all vacua stopped at about 10^{-6} Pa. The pumps improved continuously and in the 1930s and 40s there was considerable evidence from measurements of the rate of change of surface properties like the work function and thermionic emission that much lower pressures were actually obtained than were indicated by the IG.

At the 1st International Vacuum Congress in 1947, Nottingham suggested that the limit to the lowest measurable pressure was not caused by the pumps, but by an X-ray effect in the IG: He proposed that soft X-rays, produced by electrons impinging on the anode, released photoelectrons from the ion collector; this photocurrent was indistinguishable in the measuring circuit from the current due to positive ions arriving at the ion collector. This hypothesis was soon confirmed by Bayard and Alpert [1] who reduced the size of the ion collector from a large cylinder surrounding the other electrodes to a fine wire on the axis of a grid anode. This elegant solution reduced the lowest measurable pressure by a factor of 100 and is still the most common design in today's commercial IG: The Bayard-Alpert gauge or just BA gauge.

The history of the so-called cold cathode ionisation gauges is briefly outlined in section 3.2.

3. THE DESIGN OF TODAY'S MOST COMMON IONIZATION GAUGES

3.1 Introduction

The design of an IG must reply to four questions:

1. *How are the electrons produced?* Mainly, the electrons can be emitted from a heated wire or are being produced by discharge in a crossed high electric and magnetic field. These two types of electron production lead to two different types of ion gauges. It has become common notation to call the first one hot-cathode ionisation gauges (HCIG) and the latter cold-cathode ionisation gauges (CCIG). However, this distinction is no longer clear, because there exist nowadays so called hot-cathode ionisation gauges which have a field emitter source that operate at room temperature. Usually these field emitters are arrays manufactured from a silicon chip. The design of these gauges, however, is the same as in the true HCIG. It seems therefore to be better to distinguish between 'emitting cathode gauges' and 'crossed-field gauges' or 'discharge gauges'.

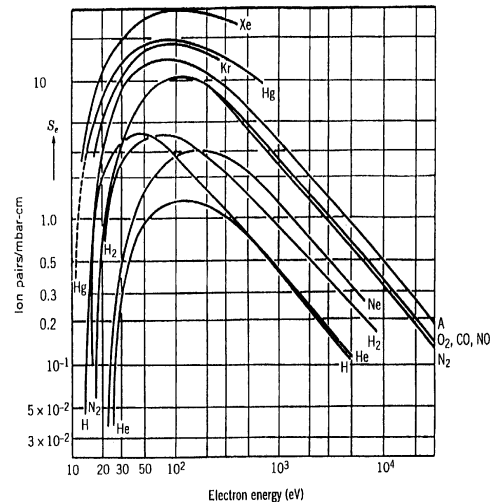


Fig. 3 Generated ions per cm electron path length per mbar at 20°C versus kinetic energy of incident electrons for various gases. From A. von Engel, *Ionized Gases*, AVS Classics Series.

2. *How is the path of the electrons shaped?* There are long, short and oscillating paths.
3. *How is the path of the ions shaped?* There can be a direct path from the ionisation place to the collector, but also longer and indirect paths, perhaps with an energy or impulse selection inbetween.
4. *What is the position and shape of the ion collector?*

3.2 Cold cathode gauges or, better, crossed-field ion gauges

The inventor of this type of gauge was Penning in 1937. He used a high voltage of up to 2kV to generate a discharge between cathode and anode. At low pressures (< 1 Pa or so) this discharge could only be maintained, if a magnetic field crossed the electrical field. The magnetic field greatly increased the path length of an electron from cathode to anode, so that it could generate another electron by impacting on a gas molecule to maintain the discharge.

It turned out that the discharge current was almost linearly proportional to the pressure in the gauge from 1 mPa to 0.1 Pa. Due to the magnetic field the electron is prevented from going directly to the anode and moves instead in helical paths through the gauge. The ions, because of their large mass, are virtually unaffected by the magnetic field and travel directly to the cathode. Secondary electrons released from the cathode by ion bombardment serve to build up and maintain the discharge (Fig. 4).

The discharge is generally not stable in crossed-field gauges. In the early designs the discharge became erratic below 10^{-3} Pa, and was often extinguished completely at 10^{-4} Pa. Therefore better designs were invented with the aim to increase the active volume of the discharge and so reduce discontinuities.

In Fig. 4 can be seen Penning's version of 1949, where the anode was changed from a ring in his original version to an open cylinder. This geometry is now widely used in ion pumps, but only for rugged and simple vacuum gauges.

A kind of breakthrough was accomplished by Redhead and Hobson, who invented the so-called magnetron and inverted magnetron gauge, the latter earlier designed by Haefer in 1955.

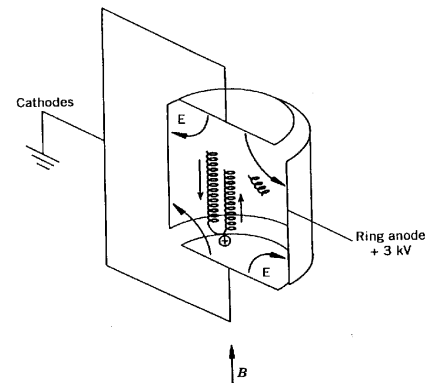


Fig. 4 Electrode arrangement, fields, and trajectories in the Penning gauge. From James M. Lafferty, *Foundations of Vacuum Science and Technology*, John Wiley & Sons, New York, 1998.

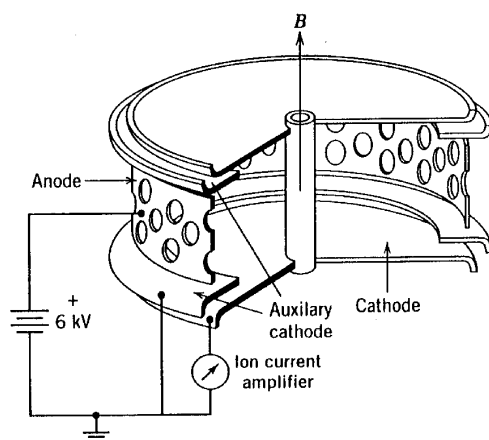


Fig. 5 Schematic diagram of the magnetron gauge. From ref. [2].

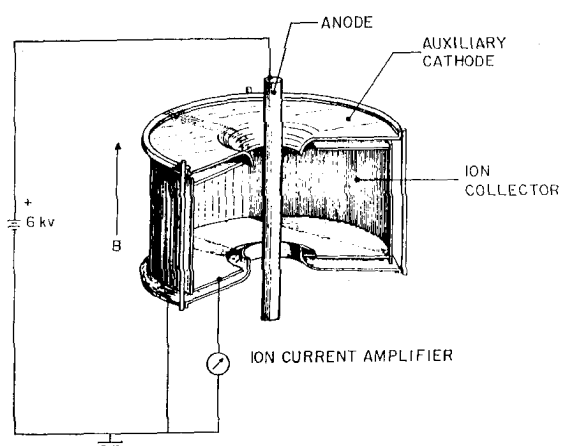


Fig. 6 Schematic diagram of the inverted magnetron gauge. From ref. [3].

In the magnetron gauge [2] (Fig. 5) the anode is an open cylinder with the cathode on axis and as endplates, in the inverted magnetron gauge [3] (Fig. 6) the anode is a rod on the axis of an almost closed cylinder as cathode. In the magnetron gauge, the end discs of the cathode are shielded from high electric fields by two annular rings held at cathode potential. Any field emission that can occur from the shield electrodes is not measured by the ion current amplifier.

One of the important features in the inverted magnetron gauge (IMG) is the use of guard rings held at cathode potential to prevent field emission currents from the cathode to the anode. The magnetic field is parallel to the anode axis. This gauge can be operated at up to 6 kV with 0.2 Tesla. In these gauges the electrons are trapped more efficiently than in the original Penning design. Due to this, the starting conditions are improved, the relations between p , B , V follow reasonably the theoretical predictions, and the discharge is stable to much lower pressures. Redhead and Hobson claimed that their gauges could be used from 10^{-11} Pa up to 10^{-2} Pa.

Almost all available commercial crossed-field gauges are of the Penning design or of the Redhead and Hobson design as Magnetron or Inverted Magnetron. Normally, at low pressures, the gauges are operated with constant voltage, measuring the discharge current, while at higher pressures (> 10 mPa) they are operated at constant discharge current with accordingly reduced voltages. Otherwise, at constant voltage, the discharge current would be so high at higher pressures that heating and sputtering of material on the electrodes would become a problem.

In crossed-field gauges, the ion current vs. pressure relationship follows the equation

$$I^+ = K \cdot p^m, \quad (2)$$

where m depends on the type of gauge and varies between $m = 1 \dots 1.4$. However, m also depends on pressure (Fig. 7) and this makes the situation rather complicated for reliable measurements. Generally, m is higher for lower pressures than for higher and may reach values up to 2. If therefore in gauge controllers the relation for higher p is extrapolated to very low pressures ($< 10^{-7}$ Pa), the gauge will indicate at these small pressures lower pressures than actually present. At pressures as high as 10^{-10} Pa this error may be an order of magnitude.

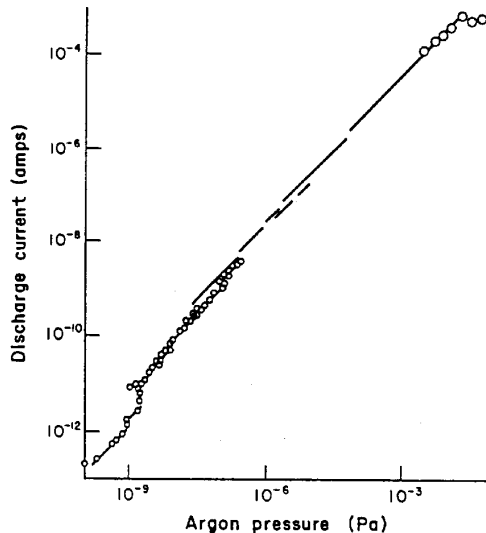


Fig. 7 Discharge current on a Penning gauge vs. argon pressure. From W.J. Lange, J.H. Singleton and D.P. Eriksen, JVST 3 (1966), 338.

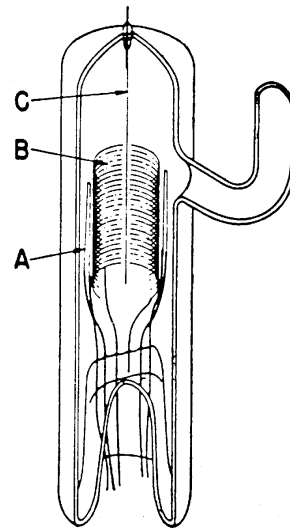


Fig.8 The original design of the Bayard-Alpert gauge. From R.T. Bayard and D. Alpert, Rev. Sci. Instr. 21 (1950), 571

Theoretical descriptions of characteristics of crossed-field Townsend discharges including electron space charge, which controls the discharge, have been given. However, Redhead [4] has pointed out that these theories have ignored the dynamics of dense electron space charge. The long trapping times of electrons allow large amplitude rf oscillations to build up. These oscillations modify

the static characteristics of the discharge and low frequency instabilities that are associated with mode jumping of the rf oscillations. Due to interaction of the electrons with the produced AC fields, excess energy electrons are generated which easily cross the magnetic field and hit the cathodes (Penning gauge) or the cathode end plates (magnetron or inverted magnetron). They falsify the discharge current or ion current. Since this effect is pressure independent it causes non-linearities in the current pressure curve. The rf oscillations may also cause serious measurement errors if unintentionally rectified in the ion-current amplifier.

In a summary comparison between crossed-field gauges and emitting-cathode gauges we will come back to this point.

3.3 Hot-cathode ionisation gauges or, better, emitting-cathode ionisation gauges

In our brief historical review we have already come to the early design of BA gauges and we will continue from there.

One of the main problems in the beginning of the BA gauge (Fig. 8) was instabilities in the gauge due to the floating potential of the glass envelope. Therefore the glass was furnished with a conductive layer which could be grounded or set to a defined positive potential. Also, it was soon noticed that ions could be lost through the open ends of the cylinder so the grid was closed at its ends to reduce this effect. The disadvantage of closing the grid seems to be that the pressure versus ion current ratio becomes non-linear for higher pressures at about 1 mPa, while this is only the case for the open cylindrical grid at pressures of 10 mPa or more [5].

In order to further reduce the X-ray limit it was tried to reduce the thickness of the collector wire. For example Van Oostrom [6] reduced its diameter to about 4 μm . Although with this method the X-ray limit is reduced, it has the disadvantage that the sensitivity is also reduced: ions formed inside the grid experience a radially inward force. Since angular momentum must be conserved, an ion with initial kinetic energy may not strike the collector wire, but rather go into orbit around it and tend to drift out axially from the electrode structure.

When the X-ray limit was reduced in this manner, another component to the background current became evident. Electrons hitting the anode may ionise molecules adsorbed on the surface causing their release. Ions generated in this manner cannot easily be distinguished from those generated in the gas phase. Since a grid structure of a BA gauge has a surface area of about 10 cm^2 the amount of adsorbed molecules can be rather high (10^{16}). Therefore it is important that the grid structure is very clean. Two measures are usually taken to cure this problem: The grid is cleaned by electron bombardment after the gauge has been exposed to high pressures or to atmosphere, and the electron current to the anode should not be too small during operation so that the gauge is continuously 'self-cleaning'.

By using the smallest practical diameter for the collector wire and increasing the sensitivity of the BA gauge by maximising the volume enclosed by the anode and using end caps the residual X-ray limit can be reduced to the low 10^{-9} Pa regime.

To measure pressures lower than 10^{-9} Pa, different approaches have been made:

- The X-ray current is measured so that it can be subtracted from the signal.
- Changes in the geometry of the gauge.
- Increasing the sensitivity by several orders of magnitude without reducing the background level.

The first two techniques have been found to be reliable and relatively easy to use in laboratory applications. The third method, however, has been disappointing, because reliable operation could not be demonstrated. Thus, there has been no widespread commercial development.

The first technique evolved when Redhead [7] suggested ion-current modulation by introducing an extra electrode into the grid space. This could be a wire close to the grid and parallel to the collector. When the wire is at grid potential, there is little or no effect on the gauge operation, but

when its potential is lowered by 100 V it seriously distorts the ion trajectories. The total ion current with the modulator at grid potential is

$$I_1 = I_r + I_g \quad (3)$$

where I_g is the current from the ions and I_r the residual current due to the X-ray effect. With the modulator at lower potential the true ion current I_g falls to $m I_g$:

$$I_2 = I_r + m I_g \quad (4)$$

so that

$$I_g = \frac{I_1 - I_2}{1 - m} \quad (5)$$

and

$$I_r = \frac{I_2 - m I_1}{1 - m} \quad (6)$$

where m may be determined at pressures where I_r can be neglected. Usually m was in the range 0.4 to 0.6, but Watanabe [8] succeeded in building a modulator gauge with $m = 0.05$.

Unfortunately it turned out that the residual current was modulated to a significant extent, because the electron trajectories were also modulated. Hobson [9] estimated that due to this, an error of $3 \cdot 10^{-10}$ Pa would be introduced in the measured pressure.

The second method of realising lower pressure measurement led, about 30 years ago, to the development of the so-called extractor gauge (Fig. 9). In this approach the ion collector is removed from sight of the grid. A simple lens is introduced between the grid and the collector to remove the ions to the collector. An ion reflector is used to reflect the ions onto the collector tip to increase the sensitivity in a way similar to that of a conventional BA gauge. In this way pressures from about 10^{-10} Pa can be measured.

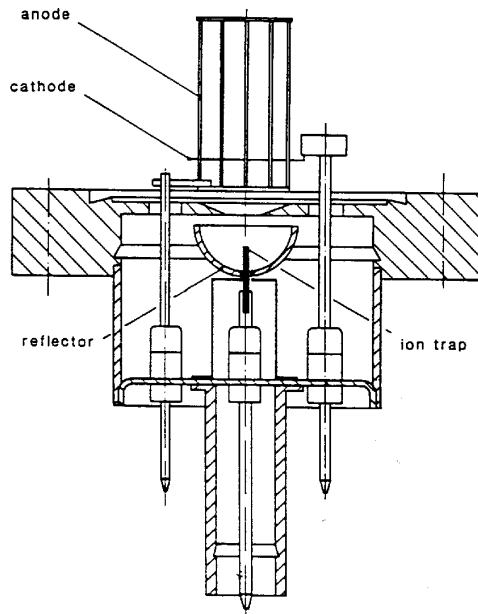


Fig. 9 Design of the extractor gauge manufactured by Leybold.

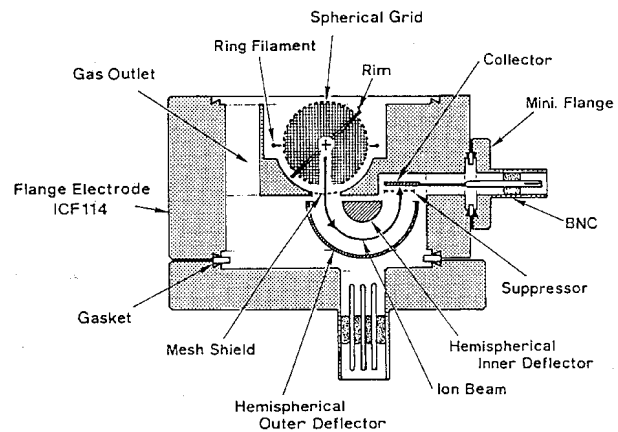


Fig. 10 Cutaway drawing of the ion spectroscopy gauge by F. Watanabe. From ref. [10].

A very sophisticated ion gauge was invented by Watanabe in 1992 [10], which he called the ion spectroscopy gauge (Fig. 10). This gauge has so many features that only the most important ones can

be mentioned. The gauge uses the extractor scheme, but with a hemispherical deflector so that the ion collector plate is completely out of sight of the grid. The collector is equipped with a suppresser electrode to inhibit electrons that are generated by reflected X-rays leaving the collector. With the hemispherical deflector where the inner electrode is at ground potential, and the outer at a variable positive potential, it is possible to separate the ions generated according to their energy. Ions which are generated at the anode grid (electron stimulated desorption effect) have higher energies than ions created in the gas phase due to a potential gradient from the grid to the extractor and due to space charge effects. The gauge uses a spherical grid in order to increase the space charge of the electrons in its centre. By this means ESD ions and gas ions can be separated (Fig. 11). Those parts of the gauge close to the hot filament could be outgassed by resistive heating or electron bombardment. Additionally, the housing of the gauge was made of high-thermal-conductance materials such as copper or aluminium in order to reduce warming of the gauge, which would stimulate hydrogen outgassing. Watanabe claimed a residual measurement limit of $2 \cdot 10^{-12}$ Pa for this gauge.

Probably the most well known example for the third method of approaching lower pressure limits is the so-called Lafferty gauge [11]. Lafferty adopted the diode magnetron principle by placing the filament along the axis of a cylindrical anode (see Fig. 12). An axial magnetic field provided by a magnet outside the enclosure forces the electrons to follow circular paths and increases their path length by several orders of magnitude. The electron emission current had to be very low (10 μ A) to ensure stable operation. An X-ray limit of about $3 \cdot 10^{-12}$ Pa was calculated for this gauge.

It is not possible to mention all the approaches to reach lower pressure limits, or all designs of ionisation gauges, instead the reader is referred to text books or review articles.

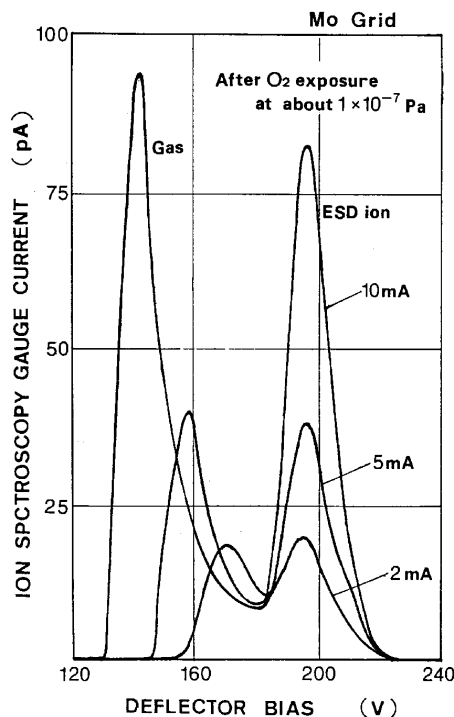


Fig. 11 Ion current vs. deflector bias voltage in the ion spectroscopy gauge after oxygen exposure at 10^{-7} Pa. From ref. [10].

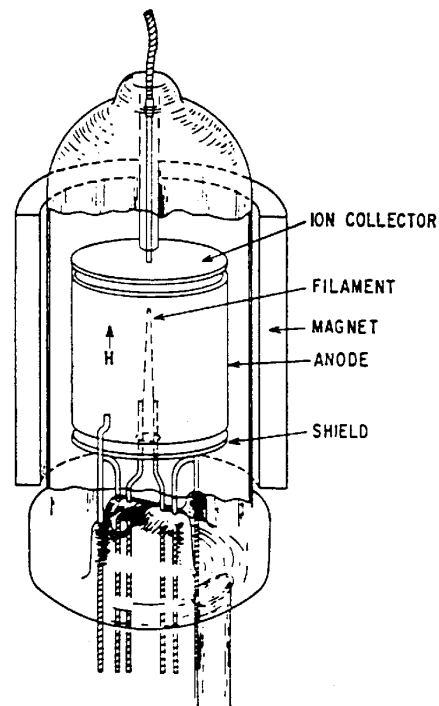


Fig. 12 Ionisation gauge designed by Lafferty to increase the electron path length. From Ref [11].

3.4 Summary comparison of crossed-field (CFG) and emitting-cathode (ECG) ionisation gauges

CFGs have the general advantage that they have no X-ray limit and electron stimulated desorption effects are small and cause little error. Also, because they already have a strong magnetic field, they are less affected by an outside magnetic field than an ECG. Where there is a suitable magnetic field,

for example in bending magnets in accelerators, this field can be used for the gauge. On the other hand, for example in electron microscopes, the magnetic field of a CFG may disturb the electron optics and must be carefully shielded.

CFGs have three generic disadvantages:

- Generally their output varies non-linearly with pressure.
- The very dense electron space charge trapped in these gauges leads to instabilities associated with mode jumping of the high-frequency oscillations.
- Their pumping speed is usually one or two orders of magnitudes higher than in ECGs and cannot be controlled.

That an ion gauge has a pumping action is a classical disturbing effect of many measuring devices, namely that it changes the value of the quantity it is designed to measure. The problems in CFGs with starting discharges at low pressures or extinction at low pressures are mostly solved in today's magnetrons or inverted magnetrons. In ECGs the electron emission current can be controlled, stabilised and varied. Mainly for this reason, ECGs are more stable and accurate, when they are conditioned before measurement.

When measuring pressures in the HV and UHV regions, a decision has to be made whether a CFG or a ECG should be bought. For this decision, the following points should be considered:

- Pressure range
- Gauge pumping speed
- Gas species to be measured
- Accuracy and stability
- Size and mechanical stability
- Interferences with magnetic fields
- Price

The available pressure ranges are very much the same for both types of gauges in the sense that there are gauges of either type for very low pressures ($<10^{-8}$ Pa) and relatively high pressures ($>10^{-2}$ Pa). However, the accuracy of the ECG is significantly better at very low pressures. But, even at higher pressures, in all CFGs discontinuities in the pressure-vs-ion-current characteristic occur and these discontinuities are not reproducible. When a calibration is repeated, they may not occur.

Hot cathodes are extremely disturbing when other than rare gases or nitrogen, hydrogen etc. have to be measured. For chemically active gases, CFGs should be used since they can be cleaned more easily than ECGs. Very important, the price of a CFG is usually lower than for an ECG.

4. PROBLEMS IN USING IONIZATION GAUGES

Suppose there is a sealed-off chamber containing pure hydrogen at room temperature and which is not pumped. An ionisation gauge is installed to measure the pressure p_1 inside it. Now let us immerse the whole chamber in liquid nitrogen. The pressure will drop by

$$\frac{p_2}{p_1} = \frac{T_2}{T_1} = \frac{77}{300} = 0.257 \quad (7)$$

but the reading of the IG will be unchanged since the gas density is the same as before. This example shows how important it is to determine also the temperature during a measurement. Even gas temperature variations caused by room temperature variations have to be considered when gauges are accurately calibrated [12].

In other cases, when a chamber is continuously pumped, the molecular flow will adjust itself such that the law of continuity holds. For example, installing a gauge with a hot cathode in a tube (Fig. 13) results in the so-called thermal transpiration effect, where

$$\frac{p_1}{p_2} = \sqrt{\frac{T_1}{T_2}} \quad (8)$$

Since the hot cathode heats up its enclosure, the temperature T_2 will be larger than in the chamber (p_1, T_1) and the pressure p_2 will be accordingly higher, but the reading of the ion gauge will be lower, because $n_2 = n_1 \cdot (T_1/T_2)^{1/2}$.

Another disadvantage of installing IG in tubes are problems associated with their pumping speed (Fig. 13). All IGs do pump, at least the ionised gas molecules, but pumping effects due to adsorption and dissociation can be much higher. If the conductance of the tube C to the IG is comparable to the pumping speed S of the gauge, the pressure in the IG is lower than that at the entrance of the tube. The advantage of installing a gauge in a tubulation is that the electrical field inside the gauge is not altered by different enclosures. Considerable sensitivity changes can be observed, when gauges are calibrated in the so-called nude configuration (Fig. 13) (no tubulation, but immersed in a large chamber) or in tubes of various inner diameters. Another advantage of tubulated gauges is that they are less sensitive to stray ions from a plasma process or other gauges.

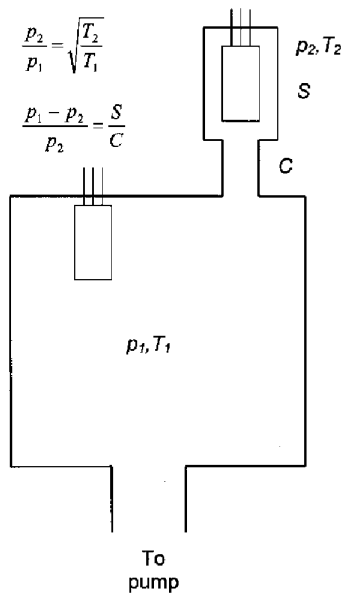


Fig. 13 Effects of tubulation of a gauge.

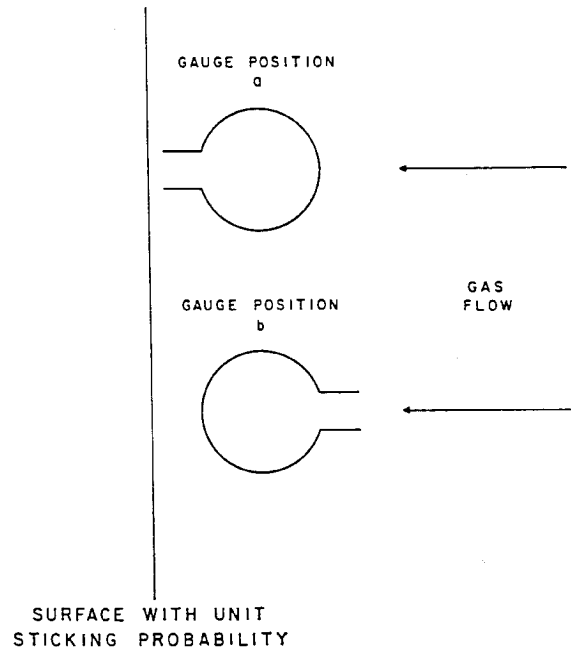


Fig. 14 Example of orientation effects when measuring gas pressures with vacuum gauges. From P.A. Redhead, J.P. Hobson, E.V. Kornelsen, *The Physical Basis of Ultrahigh Vacuum*, Chapman and Hall Ltd, London, 1968.

Other problems when measuring pressure are due to non-uniform pressure distributions inside chambers or net fluxes of molecular flow. Consider the example of Fig. 14, where gas flows from the right to the left and suppose the left wall is a cryo surface with a sticking probability of 1. The upper (a) ideal gauge (no internal gas source) will read zero, while in orientation (b) it will read an equilibrium pressure, which is determined by the differences in the rate of influx and the rate of return flow through the tubulation. Neither of these gauges gives the true pressure.

Problems with HIG arise with dissociation and enhanced chemical reactions on the hot cathode surface. For example with tungsten filaments, there is always carbon present on the surface that has diffused out of the bulk. Also, oxygen is present on its surface. Some reactions that can take place after dissociation of hydrogen are shown in Fig. 15 [13].

Outgassing and re-emission of molecules previously pumped by the gauge are significant problems in IG. A gauge operated at higher pressure will have a long relaxation time of hours or days, until a stable pressure at very low pressures is achieved. Outgassing rates of HIGs vary typically from 10^{-9} Pa l/s to 10^{-7} Pa l/s and are often the main source of gas when very low pressures must be achieved.

To obtain a reliable and long-term stable gauge reading, the gauge electrode surfaces must have a stable surface structure and composition. Not only the secondary electron yield on the collector changes with the surface composition, but also the numbers of secondary electrons generated by electrons hitting the anode grid are dependent on the anodes surface composition. Higher energy electrons (> 20 eV) also contribute to the number of ions generated in the gauge, hence the gauge sensitivity.

The gauge sensitivity depends on the gas species. Attempts to correlate this gas specific sensitivity accurately with ionisation cross sections fail due to other gas specific effects like ion capture probability, dissociation effects and secondary electron generation. Values for relative ionisation sensitivities (normalised for nitrogen = 1) presented in tables [14, 15] can be applied with some confidence while going from one gas to another, but the level of accuracy is only 10 to 20%. Where greater precision is required, gauges must be calibrated individually and for the gas in use.

As a final example of what can happen in a hot-cathode ionisation gauge (HIG), Fig. 16 shows calibrations of various HIGs, including BAG, EG, the Watanabe gauge, and BAG with gold electrodes for H_2 and D_2 [16]. Since the electronic structure of H_2 and D_2 is identical for the purpose of an IG, it could be expected that the relative sensitivity of H_2 to D_2 is exactly 1. As can be seen on Fig. 16, this is only true in some cases. Moreover, as can be seen on Fig. 17 the ratio is not even a constant for a single ion gauge. It varies with the treatment and history of the gauge. This is very surprising, since neither the potentials nor the geometry in the gauge were changed.

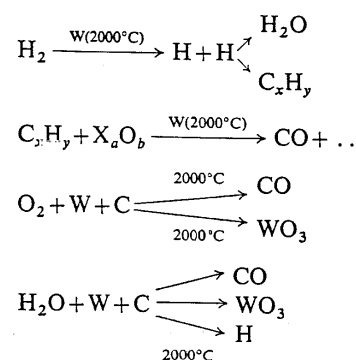


Fig. 15 Some chemical reactions which can occur at the hot tungsten filaments in ionization gauges [13].

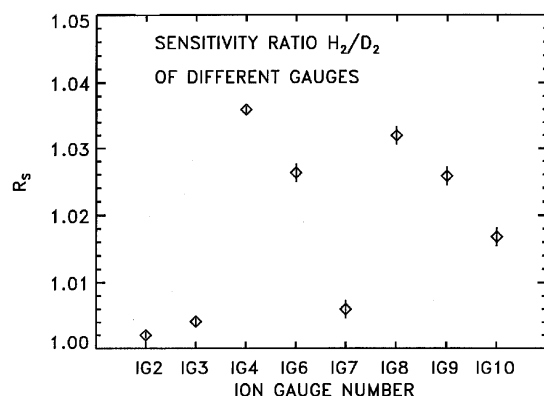


Fig. 16 Sensitivity ratio hydrogen/deuterium for various gauges. From ref. [16].

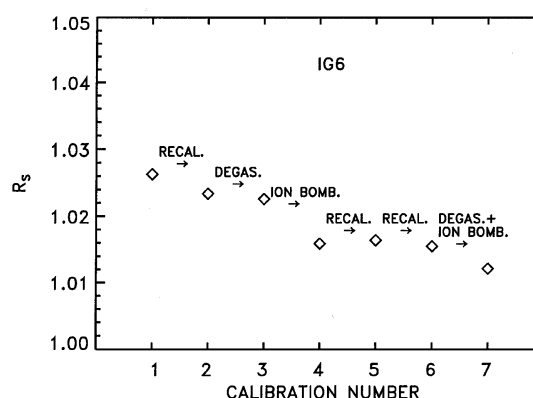


Fig. 17 Sensitivity ratio hydrogen/deuterium for a single gauge after various treatments. From ref. [16].

The reasons for the difference in the sensitivity for H_2 and D_2 is that H_2 due to its smaller mass and higher velocity in the same electric field gives a larger secondary electron yield at the collector than D_2 . This higher secondary electron yield results in a higher current on the collector and therefore a higher sensitivity. The secondary electron yield on the collector depends strongly on the surface condition, so explaining why the ratio changes with treatments and history of the gauge.

If the secondary electrons are completely repelled to the collector by applying a negative potential on a suppressor grid in front of the collector, as in the ion spectroscopy gauge of Watanabe, the sensitivity ratio for H_2/D_2 equals indeed 1 (Fig. 18).

5. IONIZATION GAUGE CALIBRATION

Most manufactures calibrate ion gauges in a rough manner before they leave the factory. This calibration gives typically an accuracy of within 20 to 50% for the calibration gas. If better accuracy is required, the ion gauge has to be calibrated with a primary standard or a secondary standard for vacuum pressures.

The calibration constant of an emitting cathode ionisation gauge is the so-called ionisation gauge constant or, less accurately, but now widely used, the sensitivity of an ion gauge. This is defined by

$$S = \frac{I^+ - I_{res}^+}{I^- (p - p_{res})} \quad (9)$$

where I^+ is the collector current at pressure p and I_{res}^+ the collector current at the residual pressure p_{res} and I^- is the electron current. Simplified equations such as

$$S = \frac{I^+}{I^- p} \quad (10)$$

should not be used, because when p is so low that I^+ is approaching its lower limit I_{res}^+ (X-ray limit, electron stimulated desorption and outgassing of the gauge) the sensitivity goes to infinity, which makes no sense (A high sensitivity is usually considered as something desirable).

In CFGs the ionising electron current cannot be measured and in this case the sensitivity is usually defined as [17]

$$S = \frac{I^+}{p^m} \quad S = \frac{I^+}{p^m} \quad (11)$$

where m is a numerical exponent. This equation for a CFG is more simple than the one for ECG (Eq. (9)), because it is assumed that there is no residual collector current (field emission, however, may occur or voltage insulation problems may be present).

It is widely assumed that the collector current of the ECG is strictly linear with pressure, hence that S as defined in Eq. (9) is pressure independent. This is generally not true. In cases, where high precision current meters are being used to determine S , typical relative variations of S of a few % are found. In cases where lower-quality current meters are used typical for built-in devices for ion gauge control units, differences of S between different pressure decades of 10% or more can be found. These differences are mainly due to imprecise resistors and rarely due to effects in the gauge itself.

The reason for the gauge inherent pressure dependence lower than about 1 mPa is unknown, but several effects may be responsible: space-charge effect may vary with pressure, secondary electron yield on the collector can be pressure dependent and also the electron emission distribution from the cathode may be pressure dependent. Above about 10 mPa it can be expected that the sensitivity will be pressure dependent due to intermolecular collisions and ion-neutral collisions, but also due to changes in space charge.

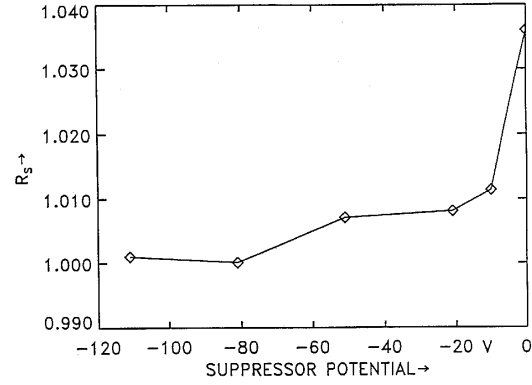


Fig. 18 Sensitivity ratio hydrogen/deuterium for the ion spectroscopy gauge in dependence of suppressor potential in front of ion collector plate. From Ref. [16].

The accuracy of pressure measurement with calibrated ionisation gauges is mainly determined by long term instabilities of their sensitivity. Typically, high quality BA gauges have long-term instabilities of 2 to 5%.

6. IONIZATION GAUGE CALIBRATION METHODS

Two basic calibration methods exist for the calibration of ionisation gauges: calibration by comparison with a reference gauge or calibration on a primary standard for high and ultrahigh vacuum pressures.

The calibration by comparison is the less accurate method, mainly because the measurement uncertainty and the long-term instability of the calibrated reference gauge has to be taken into account. The calibration by comparison has to be carried out in an apparatus that ensures that the pressure or gas density is the same at the position of the test gauge and the reference gauge. In a recent review [18] systems for calibration by comparisons have been described. If available, it is recommended that a spinning-rotor gauge is used for the calibration of an ionisation gauge between $3 \cdot 10^{-4}$ Pa and 10^{-2} Pa. It is much more accurate than the calibration with an ionisation gauge due to the better stability of the spinning-rotor gauge compared to the ionisation gauge.

The calibration of an ionisation gauge on a primary standard is the most accurate calibration method, because a primary standard has the highest possible metrological quality and deduces the pressure unit to the corresponding SI-units. Primary standards for high and ultrahigh vacuum pressures are normally pressure generators, i.e. well-known pressures with a correlated uncertainty are generated in there. The methods of pressure generation have recently been reviewed [18] together with the procedures for calibrating ionisation gauges. Primary standards for vacuum pressures are available in the major National Metrological Institutes of the world, among them the Physikalisch-Technische Bundesanstalt (PTB, Germany), the National Institute of Standards and Technology (NIST, USA), the National Physical Laboratory (NPL, England) and the Istituto di Metrologia G. Colonetti (IMGC, Italy).

REFERENCES

- [1] R.T. Bayard and D. Alpert, Rev. Sci. Instr. 21 (1950), 571.
- [2] P.A. Redhead, Can. J. Phys. 37 (1959), 1260.
- [3] J.P. Hobson and P.A. Redhead, Can. J. Physics 36 (1958), 271.
- [4] P.A. Redhead, J.P. Hobson and E.V. Kornelsen, *The Physical Basis of Ultrahigh Vacuum*, Chapman and Hall Ltd, London, 1968, p.335.
- [5] R.N. Peacock and N.T. Peacock, J. Vac. Sci. Technol. A 8 (1990), 3341.
- [6] A. Van Oostrom, *Vac. Symp. Trans. Comm. Vac. Tech., Pergamon* 1 (1961), New York, 443.
- [7] P.A. Redhead, Rev. Sci. Instr. 31 (1960), 343.
- [8] F. Watanabe, J. Vac. Sci. Technol. A 5 (1987), 242.
- [9] J.P. Hobson, J. Vac. Sci. Technol. 1 (1964), 1.
- [10] F. Watanabe, J. Vac. Sci. Technol. A 10 (1992), 3333.
- [11] J.M. Lafferty, J. Appl. Phys. 32 (1961), 424.
- [12] K. Jousten, Vacuum 49 (1998), 81.
- [13] D. Alpert, Le Vide 17 (1962), 19.
- [14] J.H. Leck, *Total and Partial Pressure Measurement in Vacuum Systems*, Blackie, 1989, Glasgow and London, p.73.
- [15] R.L. Summers, *NASA Tech. Note* NASA TN D-5285 (1969).
- [16] K. Jousten and P. Röhl, Vacuum 46 (1995), 9.

- [17] A. Berman, *Total Pressure Measurements in Vacuum Technology*, Academic Press, Orlando, 1985, p. 45.
- [18] James M. Lafferty, *Foundations of Vacuum Science and Technology*, John Wiley and Sons, New York, 1998, Chapter 12.

BIBLIOGRAPHY

A. Berman, *Total Pressure Measurements in Vacuum Technology*, Academic Press, Orlando, 1985.

Saul Dushman, James M. Lafferty, *Scientific Foundations of Vacuum Technique*, 2nd edition, John Wiley & Sons, 1962.

James M. Lafferty, *Foundations of Vacuum Science and Technology*, John Wiley & Sons, New York, 1998.

J.H. Leck, *Total and Partial Pressure Measurement in Vacuum Systems*, Blackie, Glasgow and London, 1989.

P.A. Redhead, J.P. Hobson, E.V. Kornelsen, *The Physical Basis of Ultrahigh Vacuum*, Chapman and Hall Ltd, London, 1968. This book has recently been re-edited by the American Vacuum Society.

