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LOW PRESSURE LIMIT OF THE BAYARD-ALPERT GAUGE

by

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Abstract

For many years contradictory opinions have coexisted in vacuum technology on the low pressure limitation of the Bayard-Alpert gauge. On the one hand, theory predicted that a reduction of the ion collector thickness below 0.1 mm should decrease the sensitivity such that the gain obtained through the subsequent decrease of residual current is, in the end, lost; hence, a constant measuring limit in the low 10^{-11} torr range. On the other hand, sporadic tests on gauges with collectors only a few microns thick inside closed grids, indicated that a limit one order of magnitude lower might nevertheless be achieved. Results are presented here which show that by pursuing the latter while simultaneously enhancing the gauge sensitivity (larger grid diameter and deeper penetration of electrons in the grid volume), modulated B.A. gauges with a measuring limitation in the 10^{-13} torr (10^{-11} Pa) range can be built. An interesting result of this approach is a modulation factor k (Redhead's definition) above 0.8. This important improvement in the low pressure performance of the B.A. gauge has been obtained in spite of filament induced residual currents (space charge degassing and tungsten evaporation) which can appear in the 10^{-12} torr (10^{-10} Pa) range, independently of the gauge type. As a result, a modulated B.A. gauge, characterised by a low pressure measuring uncertainty lower than 2×10^{-13} torr (2.6×10^{-11} Pa), has been selected for replacing about 400 less performing gauges of this type which are currently in use on the ISR at CERN. These existing gauges have, in fact, become obsolete due to the ISR pressure reduction into the 10^{-12} torr (10^{-10} Pa) range.

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1. INTRODUCTION

The main low pressure limitation of the ionisation gauge, since its early days, was due to photo-emission of electrons from the ion collector under the effect of soft x-rays produced by the electron bombardment of the grid. Although the drastic reduction in collector area introduced by Bayard and Alpert (1950)¹⁾ provided a decrease of this x-ray current (I_x) as well as the corresponding pressure (P_x) by two to three orders of magnitude, Alpert himself remarked some years later (1958) that it might not be possible to reduce P_x indefinitely by reducing the collector wire diameter, because "there may be a critical size of the wire below which the probability of collecting ions goes down as rapidly as does the x-ray effect"²⁾. This statement was confirmed by experimental results obtained with both open-ended and closed grids²⁾. Some years later (1965) Comsa³⁾ came theoretically to the conclusion that the low pressure limit of the Bayard-Alpert gauge (BAG) should remain constant when reducing the collector wire diameter below 0.1 mm, because the reduction of I_x might be accompanied by an equal reduction of sensitivity (S). This conclusion was based on the fact that the tangential component of the speed of the ions produced inside the grid would prevent a fraction of them from colliding with the ion collector when first approaching it. These ions could not subsequently be collected, independently of the number of their orbits around the collector, if the radial electrostatic field present in the grid volume is ideally perfect³⁾. The number of "non-collectable" ions would increase proportionally to the reciprocal of the collector diameter below about 0.1 mm - hence the constant low pressure limit³⁾. However, a systematic investigation carried out on a BAG with open-ended grid structure (Groszkowski, 1965⁴⁾) provided results in contradiction to this statement. In fact, a collector diameter reduction from 100 to 8 μ produced a decrease in sensitivity of only a factor of 5 instead of the expected 12.5.

Furthermore, already in 1961, Van Oostrom had showed that S values of about 12 torr⁻¹ for N₂ could be achieved with collector diameters as small as 4 μ ⁵⁾. The corresponding estimated P_x was below 10⁻¹² torr. This result was obtained with closed grids of 20 mm diameter made of molybdenum and tungsten collectors. It should be noted that the S value quoted by Van Oostrom required grid and filament bias voltages much higher than those normally used for BAG's (about 300 and 220 V instead of 150 and 50 V positive with respect to the collector). Schutze and Stork (1962)⁶⁾ also came to the conclusion that P_x values as low as 5 $\times$ 10⁻¹² torr are possible when using a collector of 40 μ diameter and 10 mm length.

A few years later the BAG was practically abandoned for low pressure applications upon the appearance of gauges with collector external to the grid and providing P_x below 10^{-12} torr (Clay and Melfi, 1966⁷⁾; Redhead, 1966⁸⁾; Groszkowski, 1966⁹⁾; Helmer and Hayward, 1966¹⁰⁾).

Our interest for the low pressure behaviour of the BAG originates from the need of replacing about 400 pressure gauges of this type which are at present installed on the ISR vacuum system¹¹⁾. These gauges became obsolete as a result of the vacuum improvement (from 10^{-10} to $\approx 4 \times 10^{-12}$ torr, N_2 equivalent) which has been found necessary to inhibit pressure instabilities in presence of intense proton beams^{12,13)}. The main specifications for the new gauges are on the one hand to provide pressure measurements in the picotorr range (low pressure uncertainty not higher than 5×10^{-13} torr or 6.6×10^{-11} Pa and, on the other hand, be compatible with the existing power supplies, which had been designed for modulated BAG's. This type of gauge has, therefore, been investigated in an attempt to avoid the important power supply modifications which would have been required by the choice of a different type of gauge.

2. RESIDUAL CURRENT (I_x)

For an emission current of given intensity and energy and a given choice of the grid and collector materials, it has been shown (Redhead, 1966⁸⁾) that I_x is proportional to the so-called "geometric factor" $G_2 = (2A_c / \pi A_g) f_2(a)$, where A_c and A_g are the collector and grid areas respectively, and $f_2(a)$ is a smooth function of the ratio of the grid radius to the grid length. When changing the energy of the ionising electrons by varying the potential difference between grid and filament (V_{gf}), I_x varies proportionally to V_{gf}^n , with n ranging between 1.15 and 1.8 in the various references (see for example reference 14). Physically, the geometric factor relates to the fraction of x-rays which hit the collector, whilst V_{gf}^n relates to the global efficiency of electrons in the x-ray production process.

Another well known component (I_{EID}) of the residual current arises from collection of ions desorbed from the grid under the effect of electron bombardment (Redhead, 1963¹⁵⁾). These ions have an energy much higher (a few electron volts) than those produced from the gas phase, and their trajectories inside the grid volume are practically not affected by the electrostatic field. Usually, I_{EID} is smaller than I_x but it can become dominant if the grid is contaminated, for example by exposure to high pressures of reactive gases (Redhead, 1962¹⁶⁾). Like I_x , I_{EID} is proportional to G_2 ; however, it is differently affected by the variation of V_{gf} .

2.1 Measurements of I_r

The residual currents of various gauges of BA type, with collector and grid diameters ranging from 25 to 500 μ and 20 to 35 mm respectively, have been measured. All these gauges had tungsten collectors and molybdenum or platinum-iridium grids of practically the same length (35 to 40 mm). Figure 1 shows the results which have been obtained, with $V_{gf} = 100$ V and an emission current of 10 mA, on various vacuum systems able to reach pressures in the picotorr range (10^{-10} Pa) or lower. In this figure, the residual current $I_r = I_{EID} + I_x$ (squares) or simply I_x (circles) have been plotted versus the ratio of the collector to grid diameters D_c/D_g . Each point represents a single gauge; when more than three seemingly identical gauges have been tested, their spread is indicated by the error bars. The grid material is Pt-Ir for all the gauges with D_c/D_g below 2×10^{-3} .

From these data the following conclusions can be derived :

- the dependence of I_{EID} on D_c/D_g (which corresponds to G_2 when the collector and grid lengths do not change) closely follows that of I_x down to the lowest measured values. This fact not only stresses the mutual agreement between the two measuring techniques (modulation and V_{gf} variation) but also proves that grids of large diameters (up to 35 mm) can be properly degassed.
- The low pressure requirements for the ISR should be easily fulfilled by a modulated BAG. In fact, a gauge with a grid diameter of 35 mm and collector diameter of 0.1 mm will have $I_r = 1.2$ to 1.5×10^{-12} A (see Figure 1). Even according to the most pessimistic theoretical estimations (see introduction³⁾), this collector diameter is large enough to provide high collection efficiency, and a sensitivity of 25 torr⁻¹ (or 0.19 Pa⁻¹) should be available with a grid of this size. By combining these I_r and S values it follows $P_r \approx 5 \times 10^{-12}$ torr ($\approx 6.6 \times 10^{-10}$ Pa), and a low pressure measuring uncertainty about ten times lower (10% is approximately the uncertainty associated to the P_r value simply obtained by modulation, Hobson 1964¹⁷⁾).

All the measurements reported in Figure 1 have been carried out with the ion collector at a bias voltage of 30 V negative with respect to ground. This is to prevent collection of electrons emitted from the walls of the vacuum chamber under x-ray bombardment¹⁴⁾. When the collector is at ground potential, this "reverse x-ray" effect reduces I_r by an amount which increases with decreasing wall-to-collector distance. In the ISR mounting, for instance, (gauge inserted in a tubular connection with 60 mm diameter) the measured reduction is about 30% and 50% for grid diameters of 20 and 35 mm respectively. In practice, therefore, for normal operating conditions with ion collector at ground potential, in our case I_r will be about a half only of the corresponding value indicated in fig. 1.

3. SENSITIVITY

3.1 Ion collection efficiency

The effect of the variation of the collector diameter on the sensitivity of BAG's with open-ended and closed grids has been investigated by calibrating individual gauges with identical grids and collectors of various diameters. The open grids had 20 mm diameter, 40 mm length, 2 mm pitch. Those with closed ends had 25 mm diameter, 40 mm length and also 2 mm pitch. The end caps were formed by concentric circles 2 mm apart from each other and fixed on four radial bars crossing at 90° .

The results are shown in Figure 2 where the relative sensitivities of gauges with open and closed ends (triangles and circles respectively) are plotted versus the collector diameter.

In the case of the open-ended grids the bias voltages were $V_g = 220$ V and $V_f = 70$ V positive with respect to ground (and collector) potential. The corresponding results are therefore directly comparable to those obtained by Groszkowsky⁴⁾ and indicated in Figure 2 by the full line.

The measurements on closed grid gauges have been carried out with lower accelerating voltage ($V_g = +150$ V and $V_f = +50$ V with respect to ground) in the attempt at keeping I_x as low as possible.

The uncertainty on the various measurements, of the order of 10%, is not indicated for single gauges. The error bars represent the spread of sensitivity as resulting from gauges seemingly identical (standard deviation for about 20 gauges of both types about 9% of the average value).

The difference in behaviour of the two gauge types is striking. In the case of grids with open structure, the results agree very well with those obtained by Groszkowsky and confirm that a reduction of collector diameter affects catastrophically the collection efficiency of the produced ions. In contrast, a closed grid structure provides a constant sensitivity (within the measuring accuracy) down to collector diameters as small as 25 μ . A clear decrease of collection efficiency now only appears below this value (about 50% at 10 μ). Similar results have been obtained for grid diameter of 35 mm.

An interesting by-product of the use of very thin collectors is the high modulation factor k (Redhead's definition, $k = 1 - I_2/I_1$, where I_1 and I_2 are the ion collector currents with the modulator at grid and ground potential respectively). Values of k between 0.8 and 0.9 have been achieved, reproducibly

on large numbers of gauges, for collector diameters of 25 and 50 μ and one or two modulators 0.5 to 0.7 mm thick. The obvious reason for this result is that the ions are trapped by a very thin collector only if they have no other place to go. The presence of a modulator at ground potential provides these ions an escape possibility similar to that provided by a hole in the grid structure, and in both cases the collection efficiency of the ions is greatly (and similarly) reduced. This high modulation factor also permits one to measure the collection efficiency for a given gauge in a direct way (i.e. independently of both the gauge calibration and the spread of sensitivity existing for seemingly identical gauges). In fact, the ion current collected at high pressure by the collector and modulator(s) together can be, in this case, taken as an indication of the total number of the ions produced inside the grid volume. The ratio of the ion collector current to this total ion current is then a valuable estimation of the collection efficiency in normal operating conditions. The efficiencies so obtained agree closely with those indicated in Figure 2 : for collector diameters down to 25 μ and closed grid structure, more than 90% of ions produced are normally collected.

3.2 Ion production

For a given collection efficiency the sensitivity of a gauge can be increased by enhancing the rate of ion production inside the grid volume. The latter quantity depends on the ionisation cross-section for the various gases and on the average length of the electron path inside the grid. Fortunately, the ionisation curves for the common gases all present a broad maximum between 100 and 120 eV, energy at which the x-ray effect is reasonably low. The electron path length inside the grid, on the other hand, depends on the probability that the electrons be captured when crossing the grid, on the shape of the electron orbits and on the grid size. Apart from the capture probability, which has already been extensively investigated (Groszkowski, 1968¹⁸⁾, Pittaway, 1970¹⁹⁾), some effort was devoted to analysing these points, with the following results :

3.2.1. The grid diameter was varied from 20 to 35 mm. The upper limit to this variation was dictated mainly by practical considerations (available room and grid stability during degassing) as well as by the need to insure sufficient grid heating by electron bombardment to keep I_{EID} low. All these requirements were fulfilled (see also section 2) with

the larger size, and this has finally been adopted for our application. Good statistics have been obtained for grid diameters of 25 and 35 mm (30 and 60 seemingly identical gauges, respectively), which gave S values for N_2 of 27 ± 3 and 42 ± 2 torr⁻¹ (or 0.20 ± 0.02 and 0.32 ± 0.015 Pa⁻¹) in the two cases for $V_{gc} = +150$ V and $V_{fc} = +50$ V (V_{gc} and V_{fc} represent the difference of potential between grid and collector and between filament and collector, respectively).

3.2.2. The maximum length of the electron path inside the grid is obtained when the electrons cross the grid with an incidence angle of 90° . This angle, which for an unperturbed electrostatic field is conserved for all the grid crossings, allows electrons to make diametral orbits (this statement is rigorously valid only for gauges with external collector, but it represents a reasonably good approximation also for BAG's with very thin collector). According to Redhead (1969)²⁰⁾ and Pittaway (1970)¹⁹⁾ this condition is fulfilled when the filament potential is the same as that which would exist in absence of filament at the point where it is located. Under this condition the electrons move radially in the electrostatic field which exists between the grid and the vacuum system walls. For a grid of 35 mm diameter and a grid to filament distance of 3 mm and for the chosen V_{gc} and V_{fc} values, (+150 and +50 respectively), the optimum diameter of the tube around the gauge is 47 mm. Figure 3 shows the results obtained when varying V_{gf} for such a set of parameters and tube diameters of 47 mm, 60 mm and infinity (nude gauge inserted in a vacuum system of large size). Note that the sensitivity variation for these various situations is relatively small. However, the absolute value of S in the optimum situation roughly agrees with that obtained by Redhead²⁰⁾ with an electron reflector behind the filament (S for N_2 and expressed in torr⁻¹ is about twice the grid diameter expressed in mm).

3.2.3 The same result can be achieved by adjusting V_g and V_f instead of the vacuum chamber around the gauge. In this case, however, the variation of the potential difference between grid and collector can also result in a variation of collection efficiency and of penetration of the electrons inside the grid. This interference is particularly clear in Figure 4, where the results obtained with BAG's having a grid of 25 mm diameter and collectors of 10 μ and 50 μ and inserted in a tubular connection of 60 mm diameter are shown. With the 50 μ collector the S increase achieved by properly

choosing the applied voltages is of the order of 15%, more or less the same as shown in Figure 3, while in the case of the thinner collector S doubles. This different behaviour shows that in the latter case the increase of collection efficiency accounts for the major part of the sensitivity variation. This conclusion, already formulated by Van Oostrom⁵⁾, indicates that a grid structure, which is "closed" for a given collector size and set of applied voltages, can allow ions to escape in a different situation. Should a collector diameter of $10\ \mu$ or lower be necessary for a given application to reduce I_r without varying S and grid and filament voltages, the compromise between grid transparency for electrons and ions should be reinvestigated and optimised.

3.2.4 On the basis of these results it appears that the ISR specification can be largely fulfilled. The gauge which has been finally selected has collector and grid diameters of $50\ \mu$ and $35\ \text{mm}$ respectively, $I_r = \approx 4 \times 10^{-13}\ \text{A}$ with the collector at ground potential, $S \approx 42\ \text{torr}^{-1}$ ($0.32\ \text{Pa}^{-1}$) for N_2 and consequently $P_r \approx 10^{-12}\ \text{torr}$ ($\approx 1.3 \times 10^{-10}\ \text{Pa}$) for the available voltages and a surrounding tubular connection of $60\ \text{mm}$ diameter. Sensitivity values up to $60\ \text{torr}^{-1}$ ($0.45\ \text{Pa}^{-1}$) have been reached by varying the geometry of the vacuum system around the gauge and/or properly choosing V_g and V_f . The selected gauge in its standard operating conditions presents a low pressure measuring uncertainty, as resulting from I_r , smaller than $2 \times 10^{-13}\ \text{torr}$ ($2.6 \times 10^{-11}\ \text{Pa}$).

A P_r value of approximately $5 \times 10^{-13}\ \text{torr}$ ($6.5 \times 10^{-11}\ \text{Pa}$) has been obtained with collector and grid diameter of $10\ \mu$ and $25\ \text{mm}$ (see Figure 4) and, by extrapolation, it can be estimated that a further reduction (about 50%) should be available when enlarging the grid of this gauge to $35\ \text{mm}$.

4. FILAMENT EFFECTS

During the operation of a gauge the filament not only produces electrons, but also metal atoms and heating. The consequence of these secondary effects can be not only a more or less wrong pressure reading but also a perturbation of the pressure to be measured. Both metal sublimation and heating could be particularly important for pure tungsten filaments, which work at temperatures above 2000°C . In this case, furthermore, the filament temperature is high enough to provide thermal dissociation of the H_2 molecules which reach it, resulting in a noticeable pumping action.

For the ISR application pure tungsten has been judged preferable to thoriated or thorium coated tungsten as filament material for various reasons. First, tungsten provides a constant power dissipation, whilst in the alternative case this quantity tends to increase with time, with the consequence that the behaviour of the gauge after a few years' operation is not necessarily the same as resulting from preliminary calibration. Furthermore, the emission circuits of our power supplies are designed for tungsten filaments.

The achievement of low pressures implies the use of large pumping speeds, making the pressure perturbation due to filament pumping or degassing negligible. The same is not valid for effects resulting in pressure independent gauge signals, which, furthermore, are not directly measurable during normal operation, like, for instance, what can be done for I_x and I_{EID} by modulation. The presence of filament induced residual currents could therefore completely spoil the advantages which have been achieved by using thin collector, and even more generally, external collector gauges.

4.1 Tungsten vapour

Already in 1954 Alpert and Buritz²¹⁾ came to the conclusion that the atomic tungsten which sublimates from the filament could limit the gauge reading to about 10^{-12} torr. More recently (1974) B. Angerth and Z. Hulek²²⁾ have experimentally confirmed this conclusion for gauges of BA and external collector type. We have also obtained a direct confirmation of this limit, because 7 gauges of the Helmer type, which were unable to provide pressure indications below 2×10^{-12} torr (2.6×10^{-10} Pa), have repeatedly indicated on the same vacuum systems pressures in the low 10^{-13} torr (10^{-11} Pa) range after replacing the pure tungsten (W) filament with a thoriated one. The gauge signal produced by the tungsten sublimation is clearly pressure independent and can therefore be considered as a residual signal (we will indicate with I_W and P_W the corresponding current and pressure).

Obviously, I_W can be reduced by decreasing the operating temperature of the filament, for instance by reducing the emission current and/or increasing the filament length. For a given rate of W sublimation, furthermore, the amount of W atoms which cross the grid, and can therefore contribute to the collector current, depends on the angle subtended from the filament to the grid, and decreases on increasing the grid to filament distance. Finally, for such a given angle, a larger grid will yield a lower P_W by reducing the ratio of tungsten atom to gas molecule densities in the grid volume.

All these considerations have been combined in the design of the gauge selected for the ISR. The operating emission current is about 4 mA, and the filament has a hair-pin structure which provides a total length of about 6 cm. The filament to grid distance is 3 mm and the grid diameter 35 mm. The W limit has been investigated by comparing the reading of ISR gauges, mounted on a system able to reach pressures in the low 10^{-13} torr range, with the pressure indicated by a gauge of the Helmer type equipped with thoriated filament. The few gauges so tested did not show any limit within the measuring uncertainty (about 2×10^{-13} torr or 2.6×10^{-11} Pa) even when working at an emission current of 10 mA. We therefore conclude that at the chosen emission current of 4 mA, P_W is not higher than 10^{-13} torr (1.3×10^{-11} Pa).

4.2 Operation at low V_{gf}

About 25 seemingly identical gauges with grid and collector diameters of 25 mm and 50 μ respectively have provided the unexpected behaviour shown in Figure 5. For an emission current of 10 mA, the collector current, instead of decreasing monotonically with decreasing V_{gf} , presents a minimum at about 120 V followed by a sharp increase. In this same energy range, measurements carried out at high pressure did not show any appreciable sensitivity variation.

The increase of the pressure signal on the gauge under test is accompanied by a less important but clearly noticeable pressure increase inside the vacuum system (as resulting from another gauge). The curve recovers the usual shape for lower emission current values, which also provide a smaller difference between the pressure obtained from the gauge under test (with $V_{gf} = 100$ V) and the reference gauge. Note that this difference is pressure independent and therefore represents a residual current.

The dependence of the magnitude of this effect on the emission current is indicated more directly in Figure 6. The results shown there have been obtained in a vacuum system providing pressures in the low 10^{-13} torr range (10^{-11} Pa). The pressure indicated on the vertical axis is the pressure measured by the gauge corrected by modulation. For 10 mA emission current the error resulting from this effect is much bigger than that resulting from I_x and I_{EID} , and therefore it would completely spoil the advantages of this gauge model.

All the 25 gauges of this type which have been tested have shown the same behaviour, although quantitatively the importance of this effect varies from gauge to gauge as shown in Figure 7.

In the attempt to understand the cause of this behaviour, the following observations must be considered :

- the effect has not been reduced by replacing the normal tungsten filament with a thoriated one
- the spectrum of the degassing products during normal operation at 10 mA emission current and $V_{gf} = 100$ V was practically the same as what was obtained for the same gauge during electrode degassing (at 100 mA and $V_{gf} = 600$ V).
- if the emission current of 10 mA is extracted from 2 filaments instead of from the usual simple filament, the V_{gf} variation provides a curve rather similar to that which can be obtained at lower emission currents, although both filaments, if used alone at 10 mA, produce degassing below $V_{gf} \approx 120$ V (see Figure 8).

From these observations it can be concluded that this degassing is not produced by filament heating but rather by electron bombardment of some part of the gauge such as the support of the helical filament, probably due to formation of excessive space charge.

All the gauges equipped with straight helix filaments have shown this behaviour when operated with $V_{gf} \approx 100$ V and 10 mA emission current. Much better behaved in this respect are gauges with hair-pin filament in which the active part is longer (the situation therefore approaches the two filament operation shown in Figure 8). In this case, the described effect appears, for the same acceleration voltage of 100 V, at values of the emission current of about 20 mA.

By combining hair-pin filament geometry and low emission current (3 to 4 mA) the N_2 pressure P_{sc} equivalent to the residual current due to space charge (I_{sc}) has been found to be not higher than 2×10^{-13} torr (2.6×10^{-11} Pa). This result has been obtained by the same method as was outlined in section 4.1 above (comparison with a Helmer gauge).

5. CONCLUSIONS

Sensitivity values as high as 60 torr^{-1} (0.45 Pa^{-1}) for N_2 have been obtained by properly choosing the geometry of the electrodes and of the surrounding vacuum chamber, for BAG's with collector diameters down to 25μ . The collection efficiency for the ions produced inside the grid volume is higher than 90%. With the grid structure which has been used for these measurements, a decrease of S to about 50% has been observed when using a collector 10μ thick. In this case, the normal collection efficiency can be almost completely restored by raising V_{gc} and V_{fc} from + 150 V and + 50 V to + 250 V and + 150 V respectively. As a consequence of these high sensitivities, values of P_r well below 10^{-12} torr (10^{-10} Pa) have been achieved.

The picture emerging from this investigation is one in which the behaviour of the BAG tends towards that of external collector gauges when progressively reducing the ion collector diameter. This reduction, furthermore, positively affects the modulation factor k , which for collector diameters of 25 to 50 μ can reach 0.9, providing, therefore, an effective sensitivity $kS = 50 \text{ torr}^{-1}$ (0.33 Pa^{-1}) for N_2^{20} .

On the other hand, it has been shown that the filament, even if thoriated, can induce residual current at low V_{gf} voltages, probably due to space charge effects which can completely upset the gauge performance. Nevertheless, the resulting P_{sc} , as well as P_w arising from atomic sublimation of the tungsten filaments, can be kept below $2 \times 10^{-13} \text{ torr}$ ($2.6 \times 10^{-11} \text{ Pa}$).

In conclusion, the global low pressure uncertainty of the BAG can be lower than $2 \times 10^{-13} \text{ torr}$ ($2.6 \times 10^{-11} \text{ Pa}$), this figure being representative more of the present capabilities in coping with extremely low pressure systems, than of a real intrinsic limitation of this gauge type..

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FIGURE CAPTIONS

- Fig. 1 Variation of I_r (squares) and I_x (dots) as a function of the ratio of the collector to the grid diameter. Error bars represent the spread as resulting from seemingly identical gauges (more than three). The electron emission current is 10 mA, the applied voltages $V_g = + 150$ V, $V_f = + 50$ V while the collector is at $- 30$ V with respect to ground.
- Fig. 2 The dependence of the sensitivity on the collector diameter for open and closed grids (triangles and dots respectively). The error bars have the same meaning as in Fig. 1 (here they both represent about 20 seemingly identical gauges). Bias voltages : for closed grids, same as in Fig. 1; for open grids $V_g = + 220$ V and $V_f = + 50$ V. The latter values are the same as used by Groszkowski whose results are represented by the full line.
- Fig. 3 Sensitivity (for N_2) variation as a function of the electron energy V_{gf} and for various mounting geometries of a gauge with grid and collector diameters of 35 mm and 50 μ respectively : curves 1 and 2 - gauge inserted in tubular connections with 47 and 60 mm diameters respectively; curve 3 - nude gauge. The filament is kept at 50 V positive with respect to ground.
- Fig. 4 Dependence of S (for N_2) on the electron energy for a gauge with closed grid of 25 mm diameter and collectors of 50 μ (open circles) and 10 μ (dots) diameters. The curves 1 to 4 represent, in order, the situation with $V_f = + 50, + 100, + 150$ and $+ 200$ V with respect to ground. The diameter of the tube where the gauges are inserted is 60 mm.
- Fig. 5 Collector current (I_c) variation as a function of V_{gf} at 10, 4 and 1 mA emission currents. The open circles and the arrows indicate the I_c values corresponding to the pressure indications obtained by modulation from the gauge under test ($V_{gf} = 100$ V) and from the reference gauge respectively.
- Fig. 6 Variation of the pressure (N_2 equivalent) indicated by the same gauge of Fig. 5 when varying the filament emission current I^- .
- Fig. 7 Histogram of gauges of the type shown in Fig. 5 and 6 ($V_{gf} = 100$, $I^- = 10$ mA). P_{sc} is given by the difference between the pressure measured by the gauges, by modulation, and the real pressure in the system.
- Fig. 8 I_c versus V_{gf} when extracting the emission current from 1 or from 2 filaments (upper curves, 10 mA; lower curves 5 mA).

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7