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PRESSURE MEASUREMENTS FOR THE ISR AT CERN

by

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The ISR vacuum system, originally designed for 10^{-9} torr pressures, works now at an average pressure about 100 times lower. We have therefore reconsidered the low pressure behaviour of the existing pressure gauges, and shown that their measuring accuracy in this new situation is completely inadequate. Much better results have been obtained by means of a different type of gauge, which was found to be suitable for 10^{-12} torr pressure measurements. The extended use of this better gauge might permit us to operate the ISR in a reproducible manner at an average pressure lower than 10^{-11} torr.

Geneva, 22nd June 1973

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1. Introduction

The Intersecting Storage Rings for protons were designed for circulating proton currents of 20 A in both rings. The original vacuum specification for the achievement of these intensities was a pressure of 1×10^{-9} torr inside the two kilometers of tubular vacuum chamber constituting the machine. In spite of the result that the 300 sputter-ion pumps (of 350 ℓ/s pumping speed for N_2) initially foreseen have provided an average pressure of 1×10^{-10} torr*) (more than 90% H_2, with traces of water, CO and hydrocarbons), unexpected pressure rises were recently limiting the beam intensities which could be provided for physics runs to 7 A in both rings1). These pressure rises are due for the most part to ion bombardment of the walls of the vacuum chamber1) and can be reduced by increasing the pumping speed per unit length of vacuum system (i.e. the number and/or the pumping speed of the pumps) and by better cleaning of the bombarded surfaces. An improvement programme is in progress in both these directions, and in particular, about 500 additional titanium sublimation pumps will eventually be installed. At the present stage of this programme, with already about 400 of these latter in operation (February 1973) an average pressure of about 2×10^{-11} torr is being consistently measured.

However, as a consequence of the original specification for the ISR project, the existing total and partial pressure gauges have been chosen for measuring in the 10^{-9} - 10^{-10} torr pressure range. The problem of the pressure measurements for the ISR must therefore be reconsidered, and we must try to answer the following questions :

1. What is the pressure obtainable, in the ISR, both now and after the completion of the present improvement programme, and/or after any other future possible modification? What is the desired measuring accuracy for these new situations?

2. What is the present measuring accuracy?

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*) All pressures will be expressed in terms of N_2 equivalent, i.e. for H_2, they will be 3 times lower than the true H_2 pressure.

3. How do commercially available pressure gauges compare with our measuring requirements?

1a. The ISR vacuum system

The ISR vacuum system, as already described[2)3)4)], consists of about two kilometers of stainless steel pipe of cylindrical (160 mm dia.) or elliptical (50 × 160 mm) cross section. With the exception of the cylindrical straight sections it can be considered as a periodical structure obtained by repetition of the two different elementary units (one for the outer and one for the inner arcs respectively) shown in Figure 1[5)].

Along the path of the beam the pressure increases parabolically from P_{1A}, P_{1B}, to P_{2A}, P_{2B}, which represent therefore the lowest and the highest pressures of practical interest in the two systems A and B. These pressures can be calculated, assuming a H_2 outgassing rate of 2×10^{-13} torr ℓ/s cm^2 (average measured H_2 outgassing for the stainless steel of the ISR vacuum system) as a function of the pumping speed S (for H_2) of the pumping station P. The results, shown in Figure 2, permit us to make the following interesting observations and conclusions:

i. the vacuum systems A and B are conductance limited at about 3 and 1.5×10^{-12} torr respectively; the ultimate pressure is practically independent of the pumping speed for values of S above 10'000 ℓ/s and it decreases by only 25% for S increasing from 2000 ℓ/s to infinity; an average pressure well below 10^{-12} torr will never be obtained unless the ISR are completely rebuilt (for example, by adding continuous pumping along the side of the vacuum chamber, or by degassing all the components at temperatures higher than 800°C and pressures lower than 10^{-5} torr).

ii. an extremely low pumping speed (about 500 ℓ/s) is sufficient to provide 10^{-12} torr range pressures at the 4 points considered in Figure 2; a laboratory investigation on the vacuum system already described$^{6)}$ and corresponding to the system A of Figure 1 has shown that this pressure range can easily be reached by means of a standard pumping station; furthermore, the sublimation pump which will be added to the central point of the considered vacuum chamber, (not present in our experiments) will certainly improve the situation.

One can thus conclude that the ISR vacuum system as it exists today is capable of operating in the 10^{-12} torr range. Operation of the ISR in this pressure range should be a realistic aim for the near future.

1b. The importance of the pressure measurements and the desired measuring accuracy

In addition to providing useful information during physics runs, accurate pressure measurements could help, in at least two different ways, to make the best use of the vacuum facilities already available in the ISR:

i. The pressure achieved after bakeout could depend on the baking procedure, particularly when Ti sublimation pumps are used; furthermore, the limit pressure obtained could increase with time due to the increasing gas concentration in the sublimated layers. Consequently even when the best bakeout procedure yet to be determined by means of a laboratory investigation can be reproduced in the machine, only an accurate in situ pressure indication could indicate when a sublimation is needed to regenerate the pumping speed of the titanium layers.

ii. At a particular point, when the pressure is anomalously high and fresh titanium layers do not succeed in reducing it to a more normal value, the pressure signal can indicate that a leak is present. The pressure gauge can then be used for localising (and eventually sealing) the offending leak$^{6)}$.

From these considerations it follows that the pressure can be successfully maintained in a given pressure range only if measuring facilities for this same range are available. Above, it was concluded that a realistic operating pressure range for the ISR is the 10^{-12} torr range (see 1a). We must therefore be able to measure pressures in this range and it would appear reasonable that the measuring uncertainty should not exceed 2×10^{-12} torr.*)

1c. Possible error sources when measuring very low pressure ($<10^{-10}$ torr)

Besides the errors always present, independently of the pressure range considered (for example due to estimation of sensitivity or uncertainties in the measurements of ion and electron currents), two kinds of errors are particularly important when dealing with very low pressures : i) the measurement can modify the pressure to be measured, and ii) the residual pressure of the gauge can be non negligible. These errors are, in general, quantitavely relevant, difficult to estimate and systematic even when averaging over large numbers of gauges. They are discussed in detail below.

Errors arising from (i)

All the hot cathode ionisation gauges are characterized by two opposing pressure perturbing actions: pumping, due to the formation of chemically active gas ions, and degassing, due to thermal effects or electron bombardment, of the various gauge components and of the surrounding vacuum chamber.

Repeated degassing rate measurements of the ISR gauges mounted in the standard position on ISR vacuum chambers (G_{A1}, G_{A2} and G_{B1} in Figure 1) gave an average value of 2×10^{-9} torr ℓ/s. The composition of the released gas, measured by observing the partial pressure variations obtained when switching the gauges on and off in the 10^{-12} torr range, was more than 90% H_2

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*) It is worth pointing out explicitly that the special requirements of the intersection regions are not considered here.

and traces of CO, CO_2 and hydrocarbons. Although the sensitivity of this method for the different gases decreases for increasing sticking probability to the chamber walls, only small variations are obtained when varying the gauge to mass spectrometer distance. Since the B.A. gauge pumping speeds, for H_2 and N_2, are about of 0.1 ℓ/s⁷⁾, below 10^{-10} torr the pumping effect is negligible and the measurement produces a pressure increase (ΔP) defined by the gauge degassing (Qg) and by the effective pumping speed (Sg) at the measuring point ($\Delta P = \frac{Qg}{Sg}$). The Sg values for the positions G_{A1} and G_{B1} and for the position G_{A2} are respectively of 800 and 100 ℓ/s for H_2; we have therefore the following pressure increases (N_2 equivalent, hence the factor 3) :

$$\text{for } G_{A1},\ G_{B1} \qquad \Delta P \simeq \frac{2 \times 10^{-9}}{800 \times 3} \simeq 8 \times 10^{-13} \text{ torr}$$

$$\text{for } G_{A2} \qquad \Delta P \simeq \frac{2 \times 10^{-9}}{100 \times 3} \simeq 7 \times 10^{-12} \text{ torr}$$

Although the gauge degassing rates are important if compared with the total degassing of the vacuum units A and B (Figure 1), which are, respectively of 5 and 3.5×10^{-9} torr ℓ/s, the error introduced at G_{A1} and G_{B1} is relatively small; the position G_{A2} on the contrary is particularly bad because not only the measuring error is very large, but also the actual pressure P_{2A} is substantially increased.

Errors arising from (ii)

The physical quantity providing the best indication about the low pressure measuring possibilities of a gauge is its "residual pressure" (RP), defined as the pressure indicated by the gauge when the surrounding pressure is zero.

For many years the X-rays photocurrent was considered to be the only source of residual pressure; more recently, Redhead discovered the presence of another contribution, due to ions desorbed from the grid by electron bombardment (EID) and proved[8)] that both these contributions could be measured by means of the modulation method. Although other contributions have been[9)] and will probably be found, the residual pressure measured by modulation (RPM) is still generally considered as synonymous of RP[10)]. In principle, according to the definition, RP could be obtained by subtracting, from the measured pressure, the real pressure existing in the system. However, the real pressure is in general estimated by means of another gauge; therefore the quoted RP values are generally simply the difference between residual pressures of different gauges. For this reason gauges of a different type, yielding in a given pressure situation the same indication, have been considered[11)] as having negligible RP.

We have approached, in our laboratories, the problem in another way: instead of looking for a reference gauge, we have succeeded in producing, by means of cryopumping, a reference pressure[12)] below 10^{-13} torr. When mounting in this situation a pressure gauge (usually limited to the 10^{-12} torr pressure range) its RP is immediately obtained, and the gauge becomes a good reference for another vacuum system. All the results presented here have been obtained by means of a "bent-beam" gauge used as a reference after having been calibrated in our cryopumping reference system. The measurement uncertainty (defined as plus or minus two standard deviations of the pressures measured by the reference gauge on the reference system) associated with all the RP-RPM(*) values reported here is 4×10^{-13} torr.

2. The existing pressure measurement situation in the ISR

The gauges with which the ISR are equipped as well as the results of their acceptance tests and the calibration facilities formerly used, have already been extensively discussed[3)].

Although designed for 10^{-9} - 10^{-10} torr pressures, these gauges have also been studied at lower pressures; the results of this study were summarised as follows[3)] :

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*) Residual pressure minus the part of the residual pressure which can be measured by modulation.

i) no deviation from linearity was found down to pressures of about 2 - 3 × 10^{-11} torr.

ii) the pressure indications given by these gauges are believed to be correct within a factor of two in the upper 10^{-12} torr range.

However, due to the increased importance of low pressure measurements, the low pressure behaviour of about 40 of these gauges has been re-examined.

The relative RP-RPM values, obtained as discussed, are shown in the hystogram of Figure 3. Two observations are worthy of note :

iii) the average value of the experimental distribution (about 6 × 10^{-12} torr) shows that the RPM is not the only component of RP and that a positive systematic error is present in the ISR pressure measurements;

iv) the hystogram cannot be fitted to any regular distribution and the statistical treatment of this information is therefore doubtful: in practice, any value ranging from 0 to 1.2 × 10^{-11} torr is equally probable.

This latest study confirms that the existing pressure gauges are already over extended in the lower 10^{-11} torr range and are completely inadequate for 10^{-12} torr measurements. The reason has to be attributed to the very high RPM figure (about 4 × 10^{-11} torr).

3. The ISR low pressure gauges

A few particular ISR regions, where high energy physics experiments take place, were designed from the beginning for pressures of 10^{-11} torr or lower. These regions have therefore been equipped with a different type of modulated Bayard-Alpert gauge, particularly suitable for low pressure measurements. The main feature of this gauge is the exceptionally low RPM average value (about 3 × 10^{-12} torr).

The results of the acceptance tests for about 30 of these gauges (LVG thereafter) when initially delivered are given in Figure 4[13]. About ten such gauges were in operation in the ISR, while about twenty were still available until recently in our laboratories for further study. They have been tested giving the hystograms shown in Figure 5. These results have been obtained when operating the gauges as recommended by the manufacturer, i.e. :

filament-ground voltage (Vfe) : 50 V
grid-filament voltage (Vgf) :100 V
collector-ground voltage (Vce): 0 V

In contrast with the results of Figure 3, the hystograms can now be fitted to a normal distribution, characterised by an average value of 4×10^{-12} torr and a standard deviation (σ) of 42%; the standard deviation of the average value ($\bar{\sigma}$) is 8%.

The uncertainty in the average pressure introduced by both the systematic errors 1ci) and 1cii) is about 1.5×10^{-12} torr[*]. When considering a single gauge the uncertainty becomes 7×10^{-12} torr, to which the contribution coming from sensitivity estimation (which cancel when averaging over a large number of gauges) and corresponding to 40% of the pressure indication (see Figure 4) must be added.

In conclusion the situation obtained by means of this type of gauge represents an improvement but is still far from being satisfactory. Nevertheless, the low RPM figure has encouraged us to investigate the possibility of reducing the RP values by optimizing the operating conditions.

3a. The variation of the grid-filament voltage Vgf

This variation has been used extensively, following the original suggestion by Alpert, as a method of determining the X-rays photocurrent of Bayard-Alpert gauges at the operating Vgf value. When plotting, on

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[*] This value could be greatly reduced by simply increasing the statistics

log-log scales, the collector current Ic against Vgf, the resulting curve, linear at high Vgf values when working at very low pressures, might decrease monotonically with Vgf, approaching some asymptotic value as the X-rays photocurrents approach zero.

A typical curve, obtained for one of the gauges under consideration, is shown by Figure 6. The most striking feature is the appearance of a minimum (Vgf ≃ 140 V) followed by a steep Ic increase when decreasing Vgf below 100 V; at this point Ic is about two times higher than the minimum value and the modulated current about ten times higher than the value corresponding to the pressure indicated by the reference gauge. Below 100 V, the pressure inside the vacuum system indicated by the reference gauge also increases, being lower than Ic but proportional to it.

All the LVG gauges tested show the same kind of behaviour, although the Vgf values corresponding to Ic minimum vary between 100 and 140 volts depending upon the particular gauge (see Figure 7).

Important variations can appear when displacing or replacing the filament. In general, the effect increases with the grid to filament distance: in one case, for a distance of 6 mm instead of the normal 3.1 mm (Figure 4), a residual pressure indication as high as 6×10^{-11} torr has been measured (Vgf = 100 V). The analysis of the desorbed gases performed in this opportunity has shown the composition accompanying the operation of degassing of the same gauge: about 75% CO, 15% H_2, 10% CO_2 and traces of water vapour and hydrocarbons.

The origin and the feature of this phenomenon are not yet completely clear, and research is in progress to clarify the situation; however, the existing experimental evidence seems to indicate that we are dealing with a local degassing produced by space charge around the filament. Further evidence in favour of this hypothesis will be discussed below (3b and 3c).

In practice, Vgf higher than 100 V could certainly reduce the disturbing effect of this phenomenon, but at least 140 V would be needed (see Figure 7) and the RPM figure would correspondingly increase (by a factor of 2 or 3), destroying the major merit of these gauges.

Fortunately, a much more important improvement has been obtained in a different way, and this dilemma has been shelved without being finally resolved.

3b. Intensity variation of the ionisation electron current

Practically all the Bayard-Alpert gauge manufacturers advise an ionising electron current (I^-) of either 10 or 4 mA. Although the choice is often not clearly motivated, it can be observed that, generally speaking, the 10 mA intensity provides a higher sensitivity (when expressed in A torr^{-1}) and is more effective in keeping the gauge clean; the reduced emission, on the other hand, results in a lower power dissipation and therefore a lower degassing rate.

When working at high pressures ($>10^{-10}$ torr) the gauge degassing is generally not too important while the contamination is more of a problem; hence the 10 mA figure is more widely used because only a limited fraction of the vacuum technological applications needs pressures below 10^{-10} torr. In our particular situation a reduced I^- looks particularly interesting because our working pressure is very low and both the degassing rate and the residual pressure might be considerably reduced. Furthermore, the quite high gauge sensitivity (27 torr^{-1} for N_2) permits us to reduce I^- without reducing dramatically the corresponding Ic values.

Figure 8 shows the comparative behaviour of the gauge previously considered in Figure 6, when working at I^- values of 10, 4 and 1 mA. The open circles represent the modulated Ic values obtained in the different situations considered, while the values which should be obtained (according to the pressure indicated by the reference gauge) are indicated on the Ic axis. These latter values are not exactly proportional to the I^- values because the emission variations modify slightly the pressure in the system.

The minimum characterising the 10 mA curve disappears at lower emissions; when calculating RP-RPM for the three situations the following values are found at 10, 4 and 1 mA respectively: 5.6×10^{-12} torr, 8.3×10^{-13} torr and 5.6×10^{-14} torr. These pressures are calculated taking into account the sensitivities measured at higher pressure (10^{-9} torr range) for H_2, and shown in Figure 9.

The effect of the I^- variation on the modulated pressures (corrected, as before, for sensitivity variations) indicated by a different LVG gauge, and not corrected for the surrounding pressure, are also shown in Figure 10. The measured pressure decreases very quickly when varying I^- from 10 to 4 mA (from about 3.5×10^{-12} torr to 7×10^{-13} torr); only a further decrease smaller than 7×10^{-13} torr is obtained when varying I^- from 4 to 1 mA.

In order to investigate the reproducibility of this behaviour, 13 of the gauges previously tested at 10 mA (Figure 5) have been retested at 4 mA emission current; the RP-RPM experimental distribution shown in Figure 11 was obtained. The average value is now 9.1×10^{-13} torr; this corresponds surprisingly well to the tungsten vapour pressure limitation estimated$^{14)}$ for these gauges at this emission (about 6×10^{-13} torr). The σ is now 65% and $\bar{\sigma}$ 18%.

Since the reduced value of I^- reduces the degassing rate of the gauge to about 50%, the average systematic error discussed in 1c i) is also decreased from 8 to 4×10^{-13} torr. The total average systematic error is therefore now 1.3×10^{-12} torr and the uncertainty of the average pressure 8×10^{-13} torr (± 2 standard deviations of the combined average effects).*)

The corresponding figure for single gauge indications is 2.4×10^{-12} torr; taking into account the error (proportional to the pressure) introduced by averaging the values of sensitivity the uncertainty becomes pressure dependent and ranges from 4.5 (at 10×10^{-12} torr) to 2.4×10^{-12} torr (at 1×10^{-12} torr).

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*) As previously observed, this value could be greatly reduced by simply increasing the statistics.

Thus we conclude that the error associated with the indication of a single gauge and deriving from low pressure effects is only slightly higher than our tentative requirements (1b ii); on the other hand, the error introduced by sensitivity estimation (and always present also at higher pressures) can be much bigger and probably little chance exists of finding a type of gauge providing a sensitivity dispersion lower than 10% (see Figure 4).

Therefore a higher measuring accuracy can only be achieved by using, for each gauge, its measured sensitivity, with the further condition that the uncertainty in measuring the sensitivity is better than 40% and that no sensitivity changes appear after calibration.

3c. Lower emission operation

A similar investigation has been carried out, on the same gauges, at 1 mA emission current. The results are then much less reproducible and the ion currents to be measured proportionally lower; we consider therefore that this possibility is not interesting for practical purposes.

3d. Two filaments operation

An extremely interesting feature of these gauges is that, generally, an improvement in RP similar to that obtained by decreasing I^- can be obtained by extracting 10 mA from two filaments (instead of one, as is usual). This effect is shown in Figure 12.

This observation is a further argument in favour of the space-charge interpretation previously suggested (3a) and, in practice, could permit us to couple the advantages offered by the two operating situations. Nevertheless, the geometry of the gauges presently employed is not favourable to this method of operation and more will be done when gauges modified geometrically to our specifications become available.

4. Conclusions

The present ISR situation, from the vacuum viewpoint, can be summarized as follows :

i) after installation of about 400 titanium sublimation pumps the pressure is below the measuring possibilities of the installed pressure gauges (1a);

ii) although the existing vacuum facilities are capable of providing an average pressure lower than 10^{-11} torr (1a) little chance exists of obtaining such pressures consistently without adequate pressure indications;

iii) average pressures below 10^{-12} torr cannot be achieved unless the ISR vacuum system is to be completely rebuilt (1a);

iv) it is possible to measure, with sufficient accuracy (3b), pressures in the 10^{-12} torr range by means of commercially available pressure gauges;

v) at least one model of such gauges, i.e. the LVG gauges considered in this report, is compatible with the existing control units (only minor modifications would be needed).

In other words, the possible replacement of the existing pressure gauges with gauges more suitable for 10^{-12} torr pressure measurements could improve the ISR pressure situation; furthermore, the new measuring system will be adequate as long as the ISR vacuum chambers have their present characteristics (geometry and degassing rate).

5. Acknowledgements

B. Angerth chose both types of pressure gauge considered in this report. Z. Hulek performed the acceptance tests of the LVG gauges[13)] (Figure 4) and, with B. Angerth, investigated the tungsten vapour limitation[14)] (see 3b).

We thank E. Jones and E. Fischer for continuous encouragement and useful discussions.

6. References

1) E. Fischer, Experience gained in the operation of the ISR Vacuum System, paper presented at the All-Union National Conference on Particle Accelerators, Moscow, October 2-4, 1972 (CERN-ISR-VA/72-39).

2) E. Fischer, Two Kilometers at 10^{-10} torr, the CERN Intersecting Storage Rings for Protons, J. Vac. Sci. Technol. 9, 1208 (1972).

3) B. Angerth, Equipment for total and partial pressure measurements in the ISR Ultrahigh Vacuum System, Vacuum, 22, pp 7-14 (1972).

4) C. Benvenuti, R.S. Calder, An application of Cryopumping to Colliding Beam Physics Experiments, Supplement to the Review "Le Vide" No. 157, pp. 29-37.

5) C. Benvenuti, Study of a cryopump for possible use on the ISR (CERN-ISR-VA/72-47).

6) C. Benvenuti, J.C. Decroux, Investigation expérimentale sur l'utilisation des jauges de pression à ionisation pour la détection de fuites, Le Vide, No. 162, pp. 243-248.

7) P.A. Redhead, J.P. Hobson, E.V. Kornelsen, The Physical Basis of Ultrahigh Vacuum, Chapman and Hall, 1968, p. 268.

8) P.A. Redhead, Modulation of Bayard-Alpert Gauges, J. Vac. Sci. Technol. 4, No. 2, pp. 57-62 (1966).

9) B. Iapteff, P.S. Choumoff, Contribution à l'étude des jauges du type magnetron à cathode chaude, Le Vide, No. 146, pp. 103-107 (1970).

10) W. Stechelmacher, B. Fletcher, Some Recent Developments in Low Pressure Measurements Using External Collector Ionisation Gauges, J. Vac. Sci. Technol. 9, No. 1, pp. 128-132 (1972).

11) P.S. Choumoff, B. Iapteff, Etude des limites inférieures de mesure de jauges à Ultra-Vide, Electronica y Fisica applicada, Vol. 14, No. 1 (1971).

12) C. Benvenuti, A Cryostat for the Experimental Optimisation of very low pressure condensation cryopumping, CERN 72-3.

13) Z. Hulek, Results of the Acceptance Test of 30 Balzers Gauges IMR 103 for the Intersecting Regions of the ISR, ISR-VA/KH/ck.

14) B. Angerth, Z. Hulek, On Tungsten Limit of Hot Cathode Ionisation Gauges, CERN-ISR-VA/72-51.

Figure 1

The two elementary vacuum units of the ISR Vacuum System : a) outer arcs

b) inner arcs

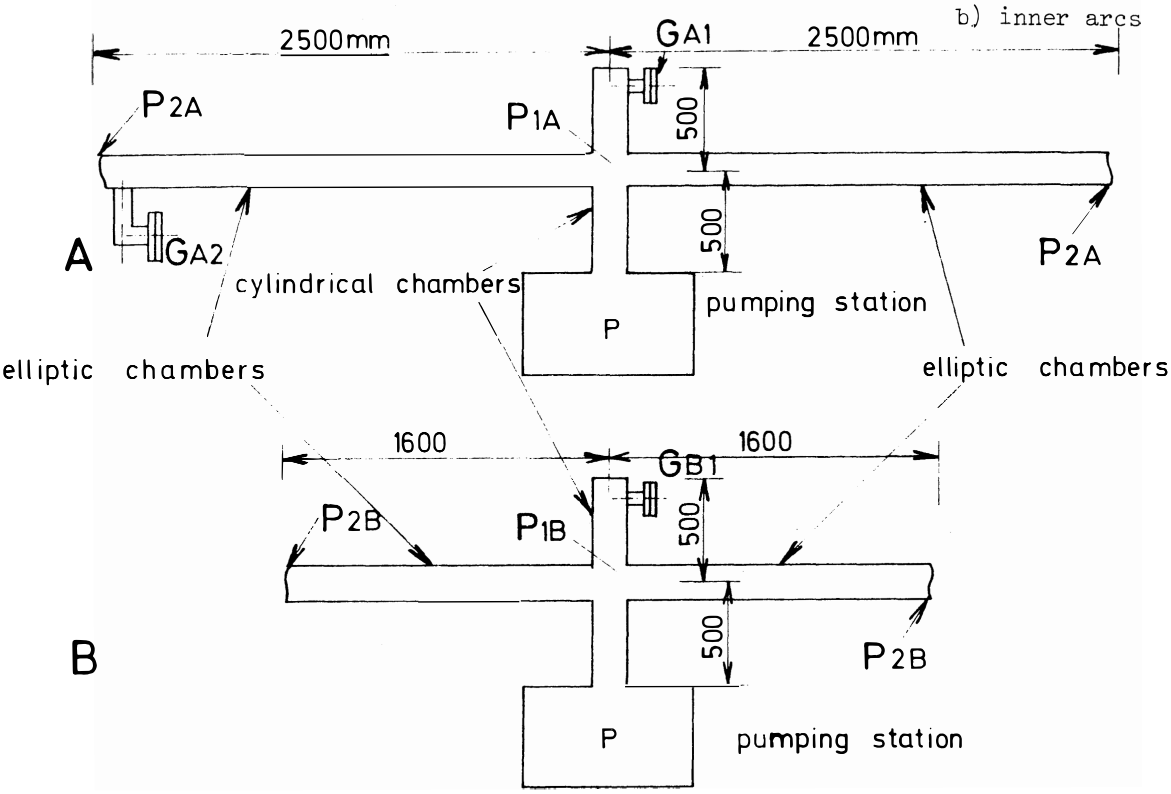

Figure 2

Pressure variation as a function of the pumping speed S at the different points of the vacuum units shown in Fig. 1

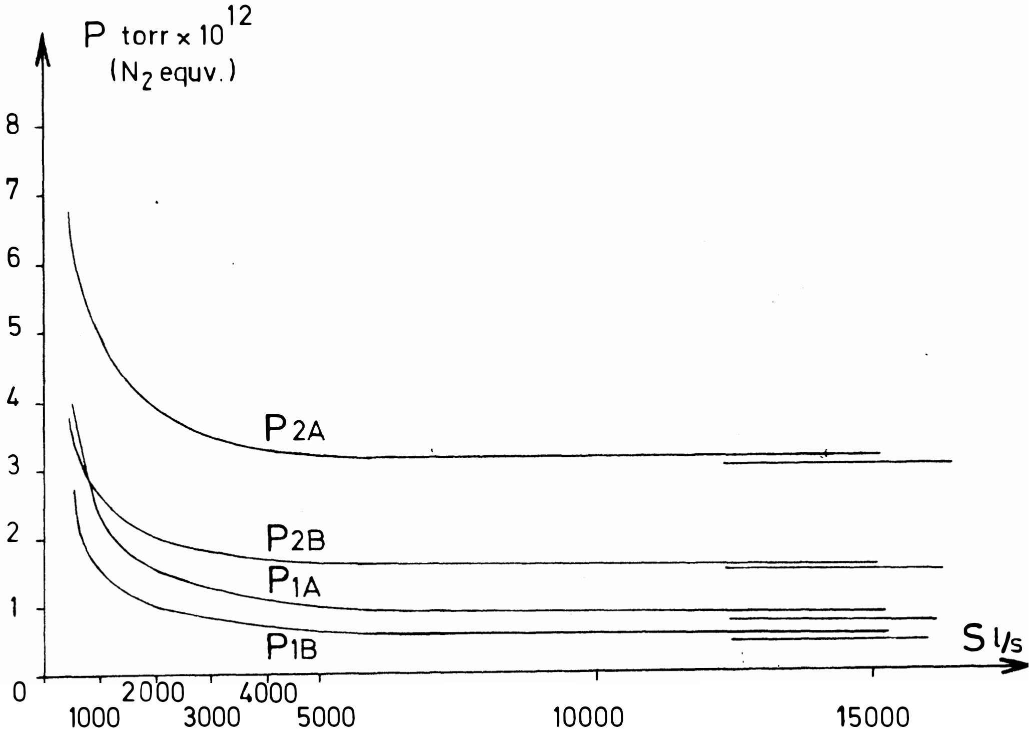

Figure 3.

Hystogram of existing ISR gauges

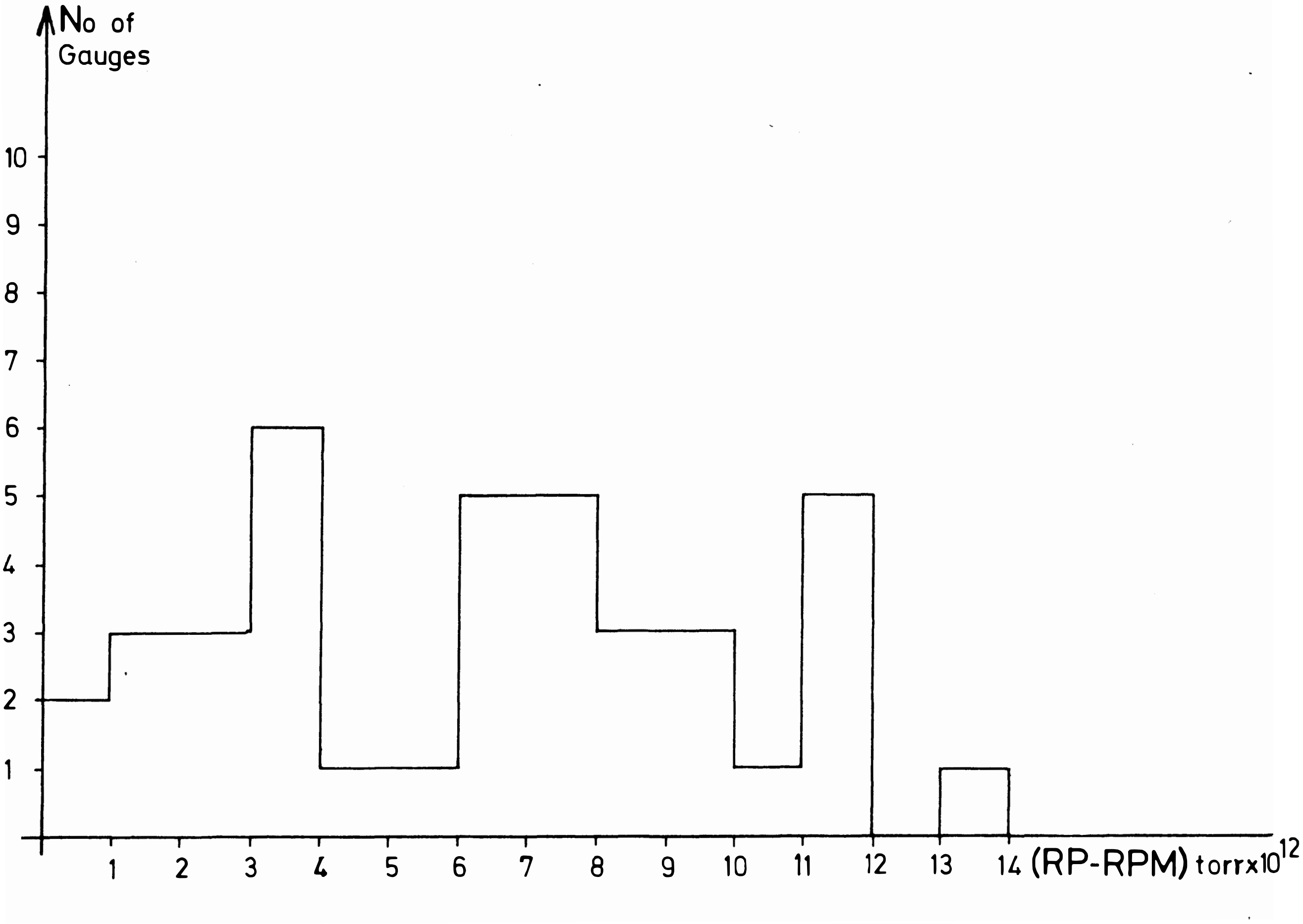

Figure 5.

Hystogram of ISR low pressure gauges (V_{gf} = 100 V, I^{-} = 10 mA)

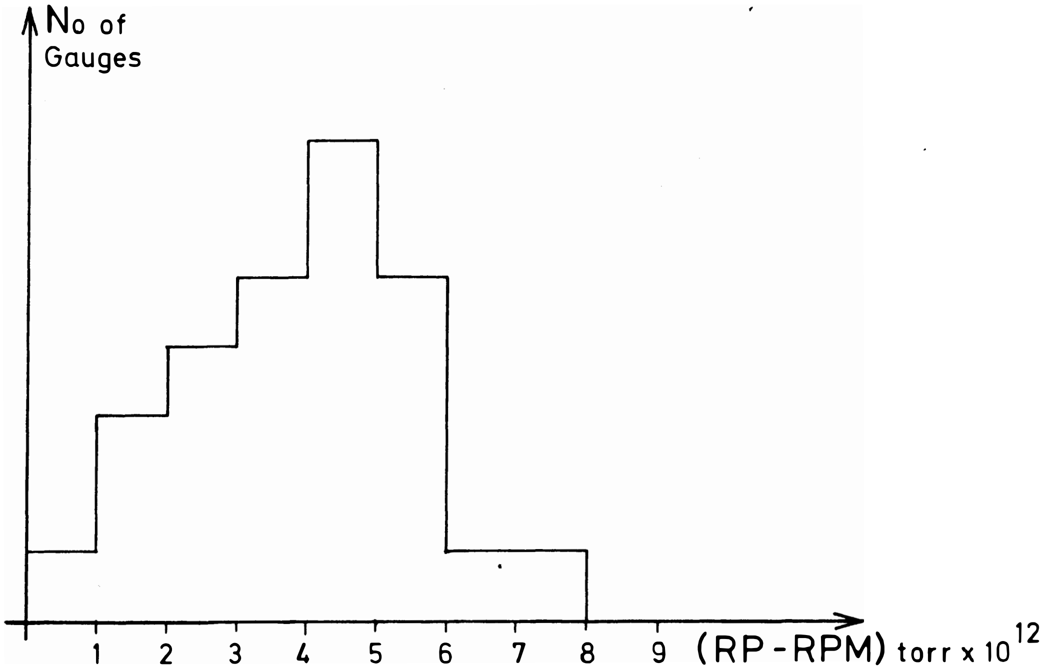

Figure 4

Results of the acceptance test of LVG gauges

Measured characteristic	$\bar{x}$	$\sigma_{\bar{x}}$%	σ_{xi}%	N
1. distance FILAMENT-GRID	3.1 mm	2.8	16	30
2. FILAMENT heating power for 10 mA emission	15.8 W			19
3. sensitivity for nitrogen	27.3 torr^{-1}	2.6	10.5	16
4. modulation factor for nitrogen	0.85	0.5	2.2	19
5. sensitivity for hydrogen	12.6 torr^{-1}	3.6	12.8	13
6. modulation factor for hydrogen	0.84	0.7	2.5	13
7. relative sensitivity for hydrogen with respect to nitrogen	0.45	2.2	7.9	13
8. ratio of modulation factor for hydrogen and nitrogen	0.98	0.2	0.8	13
9. residual collector current by modulation	1.0 x 10^{-12}A	21.3	77	13
10. residual collector current obtained by VEEM with collector at negative potential	1.0 x 10^{-12}A	5.3	19.0	13
11. reverse X-ray effect	8.4 x 10^{-13}A	6.9	24.7	13
12. residual collector current obtained by VEEM with reverse X-ray effect subtracted	1.7 x 10^{-13}A	31	112	13
13. ratio of the residual current obtained by VEEM (item 12) ot the residual current obtained by modulation (item 9)	0.21	27.3	98.4	13
14. nitrogen equivalent residual pressure reading obtained by modulation	3.7 x 10^{-12}torr	20	71	13

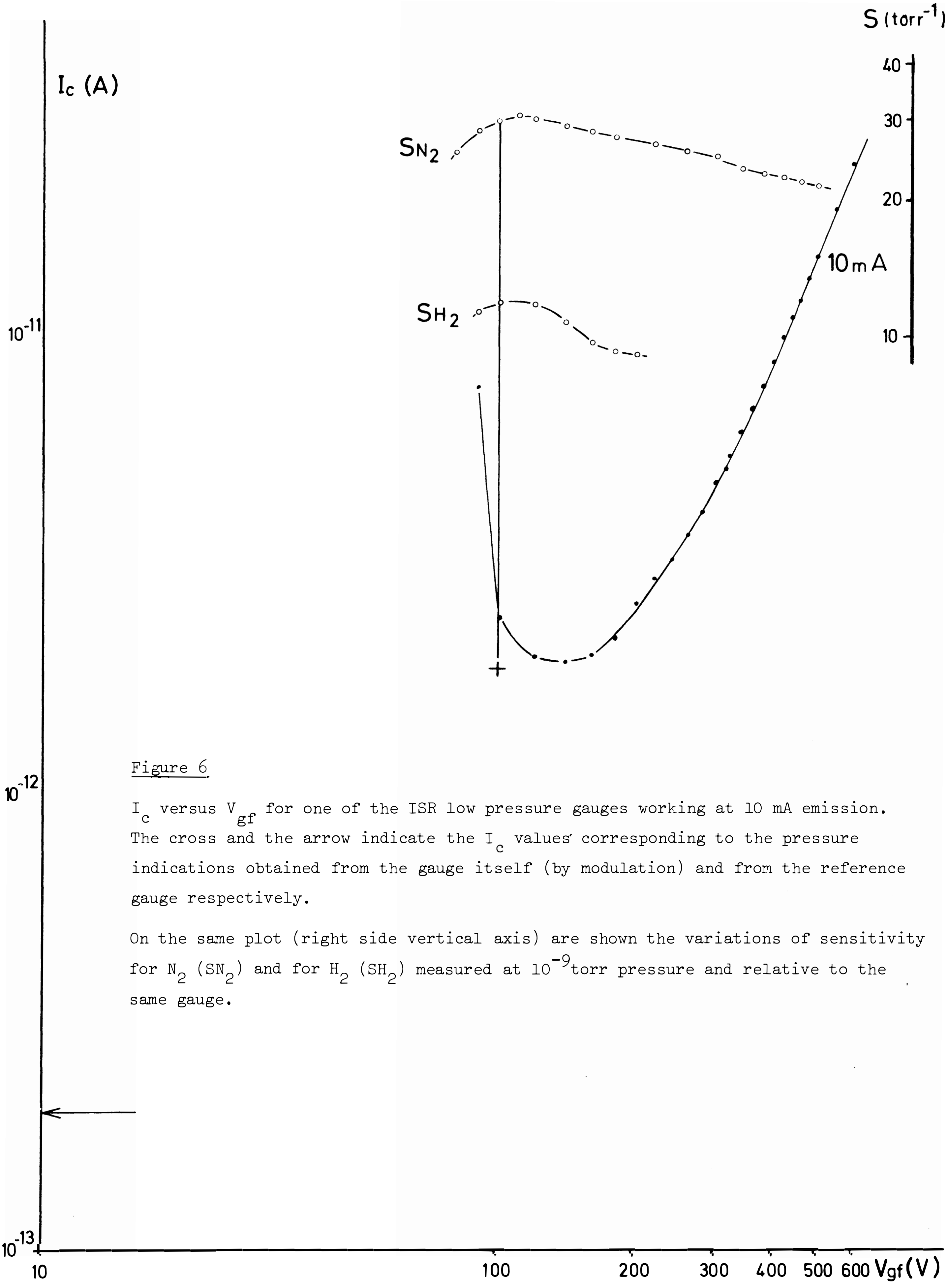

Figure 6

I_c versus V_{gf} for one of the ISR low pressure gauges working at 10 mA emission. The cross and the arrow indicate the I_c values corresponding to the pressure indications obtained from the gauge itself (by modulation) and from the reference gauge respectively.

On the same plot (right side vertical axis) are shown the variations of sensitivity for N_2 (SN_2) and for H_2 (SH_2) measured at 10^{-9}torr pressure and relative to the same gauge.

Figure 7

Hystogram of the V_{gf} values corresponding to I_c minimum for the 20 tested LVG gauges.

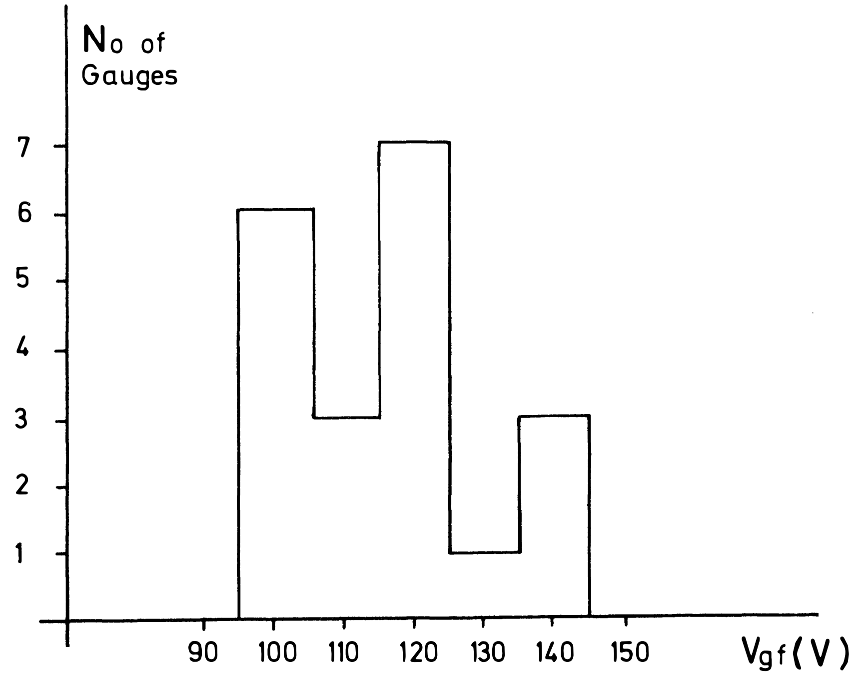

Figure 9

Sensivity ($torr^{-1}$, for H_2) variation as a function of V_{gf} at various emission currents. Results for the gauge considered in Figures 6 and 8.

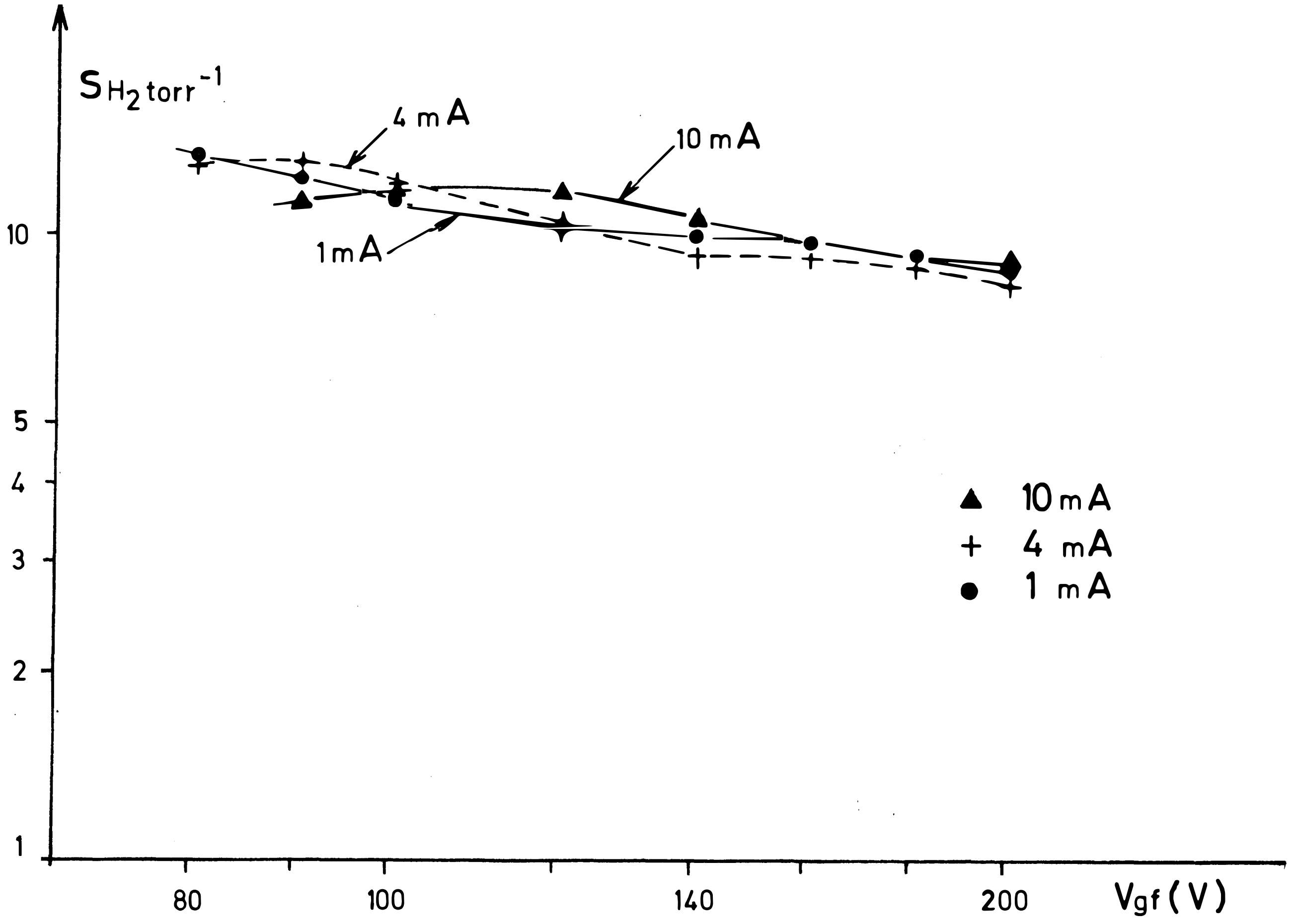

Figure 8

I_c variation as a function of V_{gf} at 10, 4, 1 mA emission currents for the gauge of Fig. 6. The open circles and the arrows indicate the I_c values corresponding to the pressure indications obtained from the gauge itself (by modulation) and from the reference gauge, respectively.

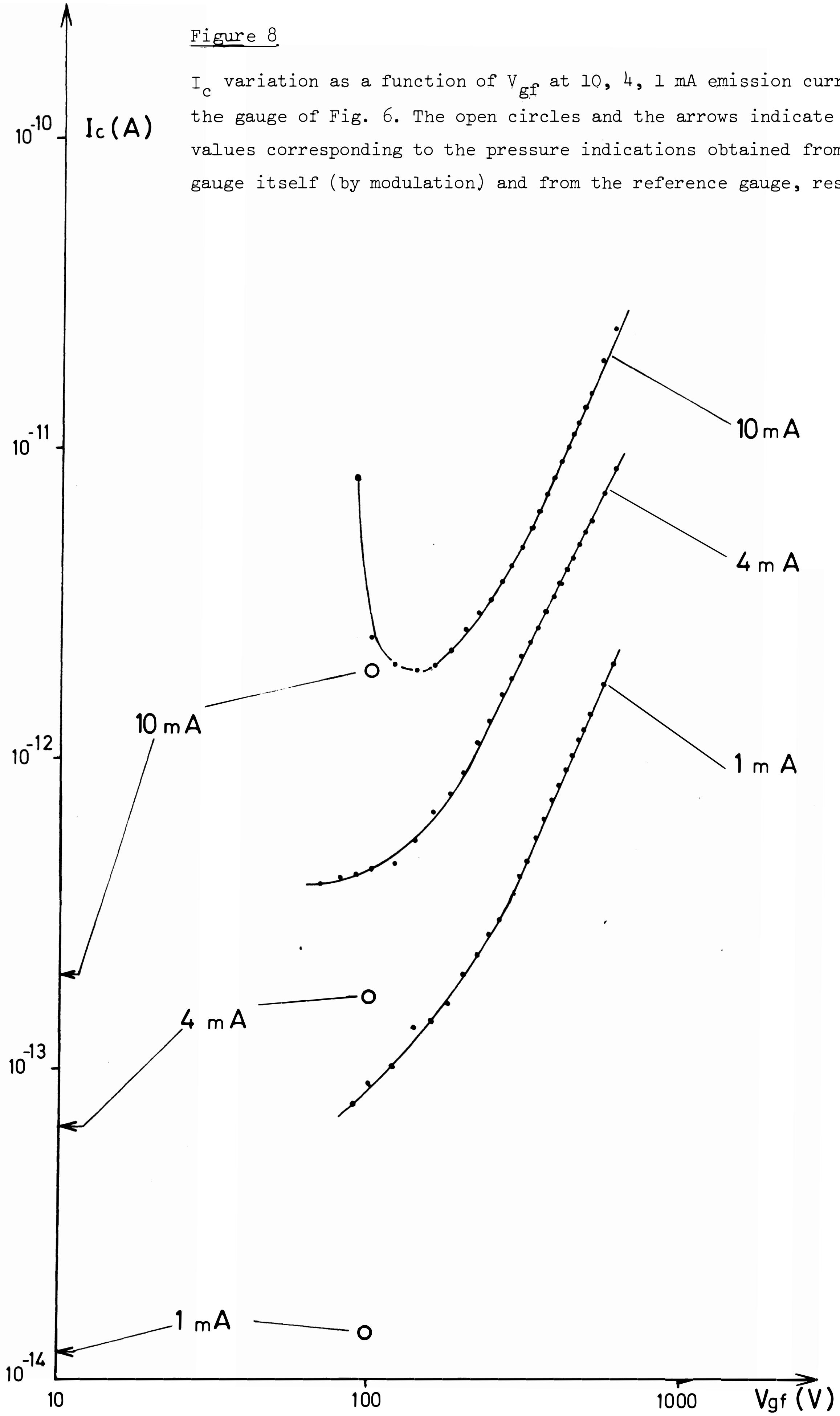

Figure 10 :

Variation of the pressure (N_2 equivalent) indicated by a LVG gauge when varying the emission current.

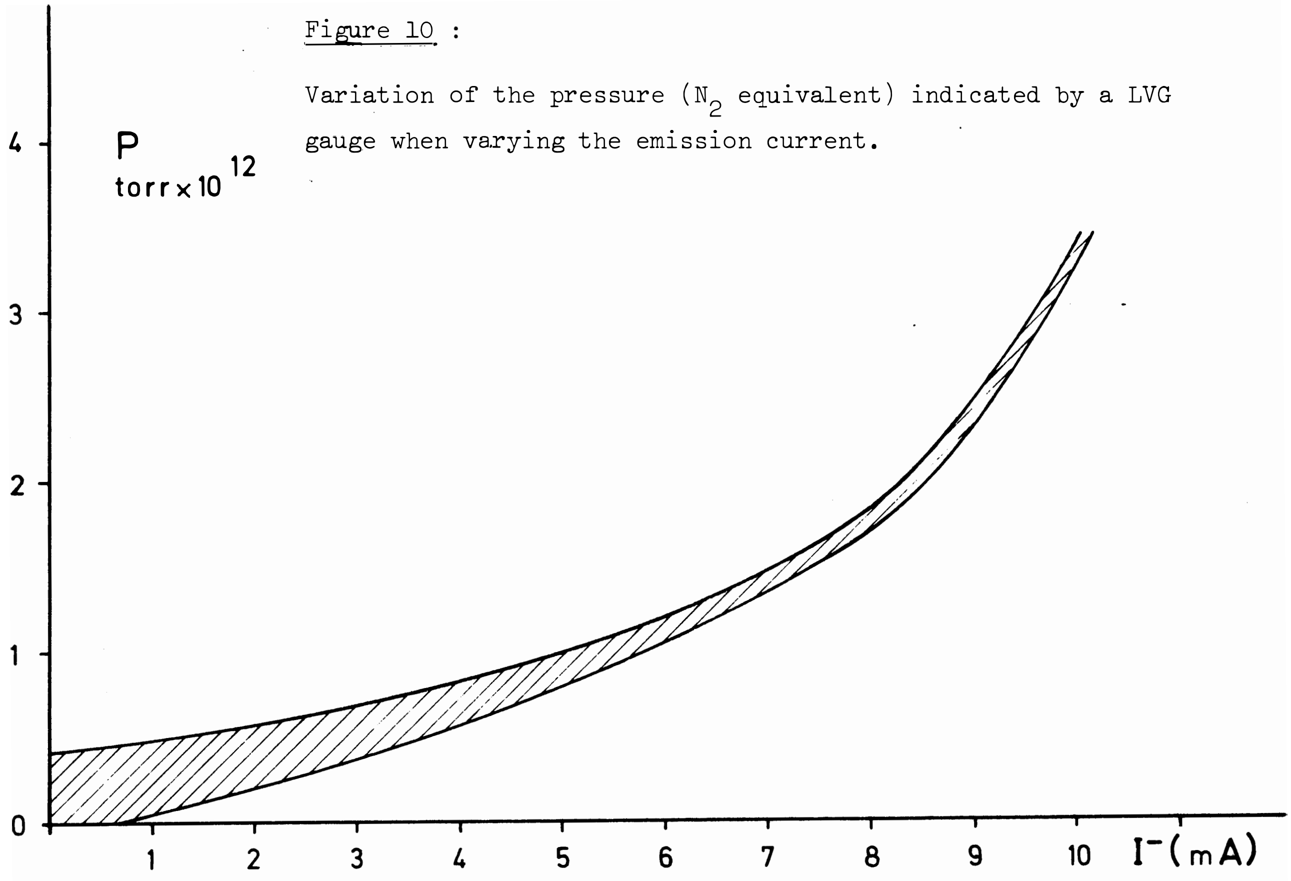

Figure 11 :

Hystogram of the LVG gauges at $I^- = 4$ mA ($V_{gf} = 100$ V).

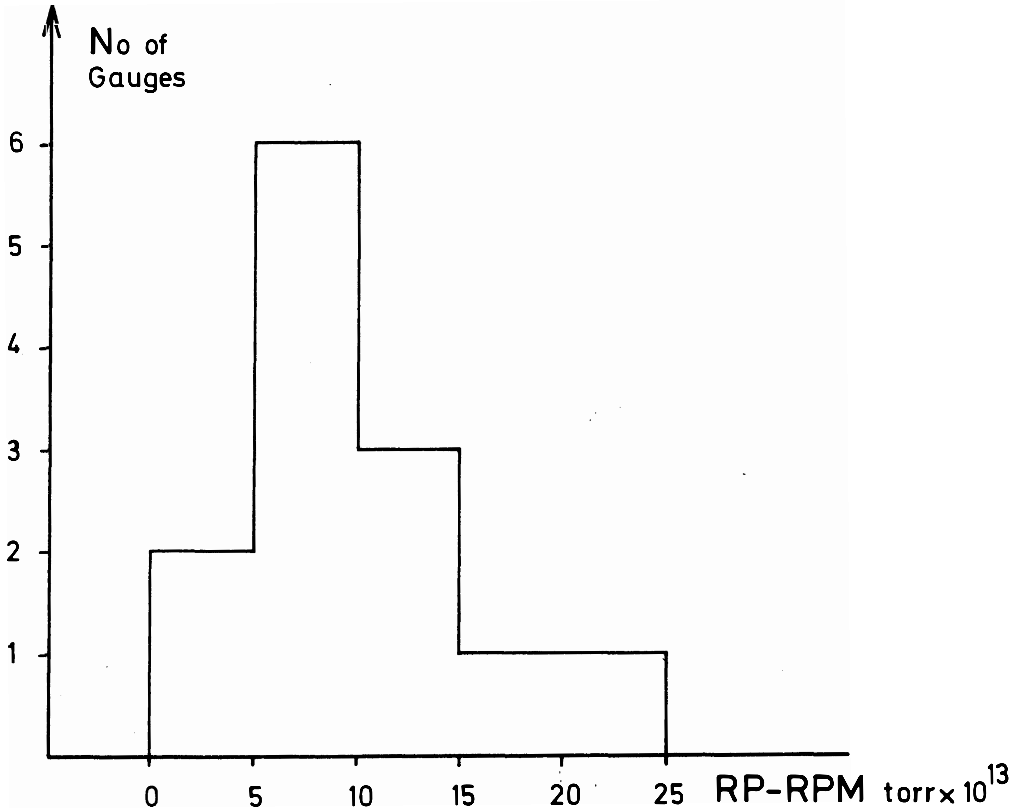

Figure 12

I_c versus V_{gf} when extracting the emission current from 1 or from 2 filaments (upper curves, 10 mA ; lower curves, 5 mA).