BEAM INDUCED GAS DESORPTION IN THE CERN INTERSECTING STORAGE RINGS

O. GRÖBNER and R.S. CALDER

ISR Division - CERN

Geneva, Switzerland

Summary

The maximum beam intensity achieved in the ISR has been limited up to now by the beam induced pressure rise which builds up with the stacked proton current. This pressure increase can be explained by ion induced gas desorption from the vacuum chamber. The pressure P, as a function of the stacked proton current I, can be described in good approximation by $P = P_0/[1-(k\eta/S)I]$, where P_0 is the pressure without beam, S the pumping speed, η the net gas desorption coefficient in molecules per incident gas ion and k is a constant. This concept shows the existence of a critical current at which the pressure goes to infinity. The desorption coefficient depends on the primary ion energy, the type of ions and above all, on the surface conditions. Surface treatments yielding low and even negative values of η are discussed together with experimental results obtained.

1. Introduction

The present limit on beam current in the CERN Intersecting Storage Rings (ISR) has been determined above all by the performance of the vacuum system. The average pressure along the 1 km vacuum pipe which has been in the low 10^{-10} torr range (and a current improvement program is reducing this even further to about 2×10^{-11} torr), yields low beam decay and blow-up rates up to moderate currents. However, when stacking to high currents one or more localised pressure rises may appear which lead to a rapid decay and, if stacking is continued, the beam gets lost due to the various types of beam instabilities or the internal dumping mechanism triggered by the vacuum interlocks. Fig. 1 shows a localised pressure bump and Fig. 2 demonstrates how this pressure grows during the process of beam stacking. This catastrophic effect, often called pressure bump or vacuum instability was observed early during the commissioning period of the ISR and has stimulated intensive studies together with a continuous effort to improve the ultrahigh vacuum system.

Several hypotheses have been put forward to explain the pressure bump mechanism but it is now well established that the pressure increase is caused by an avalanche type of process based on ion induced gas desorption from the stainless steel walls of the vacuum chamber. The ionisation of the residual gas by the beam produces an energetic ion bombardment of the chamber and causes the pressure rise by desorption of surface molecules. Since the ion production is proportional to beam current times pressure[1] one has an accumulative effect.

The following observations suggest that this sequence is indeed the mechanism of the pressure bump :

i) the pressure increase is very sensitive to the beam potential and hence to the ion energy, in agreement with ion desorption yields quoted in the literature[2].

ii) The pressure rise is proportional to beam current rather than beam loss. This excludes gas desorption by particles lost from the beam.

iii) The desorption yield for ions is of a right order of magnitude to explain the pressure rise : electron desorption yields are at least two orders of magnitude too small.

iv) The gas composition in the pressure bump is markedly different from that of the normal residual gas typically > 95 % H_2. In particular, heavier masses appear which indicate the existence of an adsorbed gas layer on the wall.

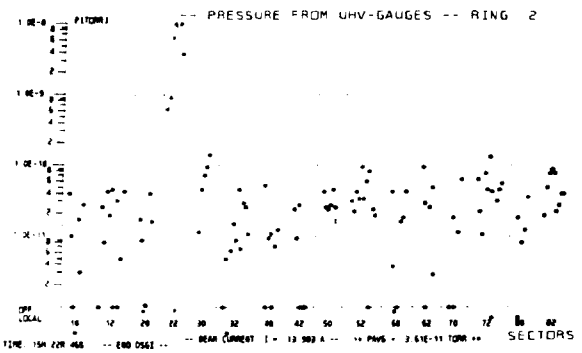

Fig. 1 Pressure distribution in ring 2 of the ISR showing a localised pressure bump in sector 22 caused by a 13.9 A. circulating beam.

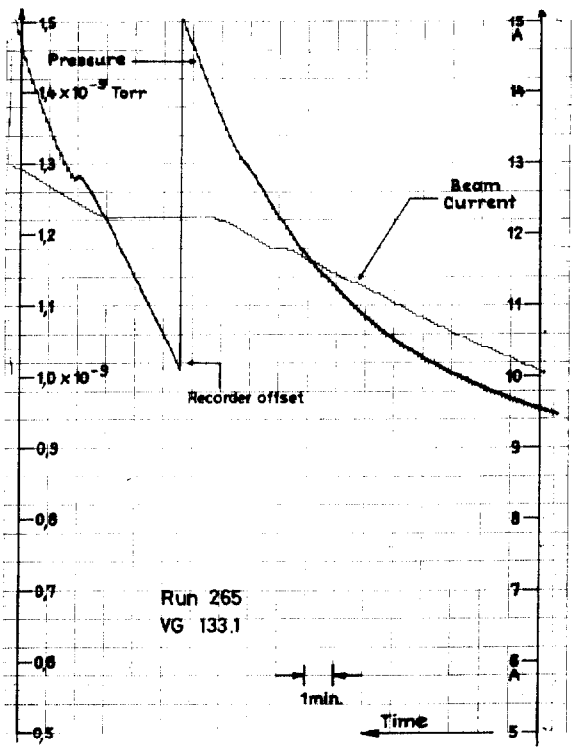

Fig. 2 The development of a pressure bump during beam stacking.

v) Beam pumping, i.e. a reduction of pressure in the presence of a circulating beam, can be observed in particularly well cleaned sections of the ISR vacuum chamber (see sect. 4 ii). This is attributed to the number of gas ions being buried in the chamber wall exceeding the number of molecules released - in effect an ion pump.

For completeness it may be added that electron desorption and desorption by beam loss have been observed but both effects play only a secondary role.

2. Theoretical

For the study of the pressure bump effect the ion desorption yield η is defined as the net number of molecules leaving the surface per primary incident ion. The total number of molecules liberated per second and per unit length is then given by $\eta\sigma in$, n being the number of gas molecules per unit volume, i the number of beam protons per second and σ the ionisation cross-section. For convenience a standard value for σ of $1{,}2 \times 10^{-18}$ cm^2 for protons of 25 GeV on nitrogen has been assumed throughout in the calculations of η - for other energies or gases a correction has to be applied.

To describe the gas density in a module of the ISR vacuum chamber this beam desorption has to be included in a dynamic vacuum equation for a distributed and conductance limited system[3] . One then obtains for $n(x,t)$

$$\left.\begin{aligned} A\frac{\partial n}{\partial t} &= g + \sigma\eta in + c\frac{\partial^2 n}{\partial x^2} \\ \text{with the boundary condition} \qquad & \\ \left[c\frac{\partial n}{\partial x} \pm Sn\right]_{x = \pm L} &= 0 \end{aligned}\right\} \qquad (1)$$

Here A denotes the chamber cross-section, g the outgassing load per unit length, c the conductance per unit length of the vacuum pipe and L the half distance between pumps of speed S. The boundary condition is derived from putting the gas flow at the end points equal to the gas pumped.

The solution of equation (1) can be obtained by separating the variables x and t and represented by a Fourier series.

$$n(x,t) = \sum_{\nu=1}^{\infty} \cos\lambda_\nu x \left\{ \frac{C_\nu}{F_\nu} + \left(B_\nu - \frac{C_\nu}{F_\nu}\right) \exp(-F_\nu \cdot t/A) \right\} \qquad (2)$$

where λ_ν are the roots of the transcendental equation

$$\lambda_\nu \tan \lambda_\nu L = S/c \qquad (3)$$

and with the coefficients

$$C_\nu = (2g/a_\nu^2 \lambda_\nu) \sin 2L\lambda_\nu$$

and

$$a_\nu^2 = L + (1/2\lambda_\nu) \sin 2\lambda_\nu L .$$

From the starting condition one finds

$$B_\nu = 1/a_\nu^2 \int_{-L}^{+L} n(x,o) \cos \lambda_\nu x \, dx,$$

where $n(x,o)$ is the initial gas distribution. The term containing the beam desorption is $F_\nu = c\lambda_\nu^2 - \sigma\eta i$. Since a finite equilibrium pressure can only exist for negative exponents in equation (2) it follows that for stability the product ηI must be less than the critical value

$$(\eta I)_{crit} = ec\lambda^2/\sigma \qquad (4)$$

Here the conversion is made from protons per second to beam current I in A, $e = 1{,}6 \times 10^{-19}$ C and λ is the first root of equation (3), $\lambda = \lambda_1 < \lambda_2 < \ldots$.

Most of the data were taken at pressure equilibrium. An approximate pressure bump equation valid for equilibrium can be derived from equation (2) by taking the first term of the series expansion only. This yields the relationship between the starting pressure P_o and the pressure in presence of beam P_I,

$$P_I = P_o/\left[1-(k\eta/c\lambda^2)I\right] \qquad (5)$$

k being written for the ratio σ/e. In analogy with a vacuum system with a lumped volume one can consider the term $c\lambda^2$ (cm^3 sec^{-1} cm^{-1}) as an effective pumping speed per unit length, S_{eff}.

The analysis neglects so far all readsorption effects which often dominate the pressure behaviour in an ultra-high vacuum system. This approach nevertheless seems justified as long as only equilibrium states are observed where one assumes that the surface coverage of adsorbed molecules is in balance with the gas phase. This simplification can no longer be used in a dynamic situation, e.g. the build up of the pressure bump. For a complete analysis it is then necessary to include the reaction of the surface to changes of pressure in equation (1).

To combat pressure bumps in the ISR the effective pumping speed at any point may be increased either by augmenting the installed pumping speed S and/or by decreasing the pump separation 2L. Equations (3) and (4) show, for a conductance limited system as the ISR, that the inter-pump distance is the more critical factor. Alternatively, one may attempt to lower η by producing cleaner surfaces. The latter solution is certainly the more elegant but until it can be shown that such clean surfaces are stable and resistant to leaks etc., the former method of increased pumping speed will obviously have the compensating attraction of security.

The first method is the basis of a current improvement program now nearing completion in which over 400 titanium sublimation pumps have been installed reducing the average distance between pumps to about 2,5 m in the low conductance magnet chambers and to about 4 m elsewhere. The expected increase of the pressure instability limit in terms of ηI is at least a factor of 5, in principle sufficient to reach the design current of 20 A. The table shows computed values $(\eta I)_{crit}$ in amperes, (A) for the earlier situation of ion pumps (S = 100 l/s) and (B) after adding sublimation pumps (S = 500 l/s) with the inter-pump distance 2L as parameter.

	2 L (m)	A	B
elliptical chamber 5 x 16 cm	5	25	37
	2,5	60	130
round chamber 16 cm diameter	10	20	47
	4	50	190
experimental region I 2	8	15	
	4		40
special chamber in injection septum magnet	8	8	
	1,6		200

It is seen that only by reducing the inter-pump distance, particularly in the case of the low conductance elliptic magnet chamber, can the full advantage of the high speed sublimation pumps be used.

In parallel with the installation of additional pumps the desorption properties of the vacuum chamber are being studied with the aim of defining better cleaning procedures, bake-out or other surface treatments yielding lower η values.

The desorption coefficient η, will depend in a rather complex way on the state of the surface and on the type and energy of the bombarding ion. For a phenomenological approach it is therefore convenient to consider η as the difference of two quantities, $\alpha_1 - \alpha_2$: α_1 being the number of gas molecules released per incident ion and α_2 the probability of the primary ion sticking to the surface. Since α_2 cannot exceed unity it follows that $\eta \geq -1$.

The desorption is likely to depend rather strongly on the surface coverage of adsorbed molecules θ, and therefore α_1 will be the dominant term for a dirty or contaminated vacuum chamber. The sticking probability α_2 on the contrary will probably be essentially independent of θ with perhaps a small increase as the surface contamination is reduced and more sites become available for adsorption. One may therefore expect an approximate overall proportionality between η and θ for high degrees of contamination with a limiting value of -1 for vanishing θ.

At moderate and high energies (e.g. $E_i > 500$ eV) the desorption term α_1 dominates and η will be roughly proportional to the primary ion energy[2]. At lower energy, especially for clean chambers, η will be determined by both α_1 and α_2. The term α_2, depending on various phenomena such as ion adsorption, backscattering and ion burial, may account for the systematically observed rapid rise of η at low energies as seen on Fig. 4 and 5. The potential of the proton beam and hence the ion energy E_i depends on beam density, beam-chamber geometry and further it is roughly proportional to the beam current. Typically one finds between 100 and 200 volts per ampere for the ISR.

Apart from the energy dependence one can observe a very pronounced intensity dependence of the desorption yield at constant ion energy - see section 4 ii and Fig. 6. This effect is not fully understood but there may be two possible explanations:

i) As the pressure bump develops the rest gas composition, originally 95 % H_2 may change appreciably by the desorption of heavier molecules. Therefore if the desorption depends strongly on the ion species this could give rise to the apparent increase of the composite η. The dependence of the cross-section σ on the gas species will also contribute to this effect.

ii) Incident ions may excite the surface molecules so that subsequent ions have a higher desorption probability giving a nonlinear behaviour of η.

3. Experimental set-up

Measurements of η have been made at various places around the ISR where pressure bumps occurred. A direct method consists in observing the initial pressure decay P_o^* at $t = 0$ after reducing instantaneously the beam current to zero (i.e. by beam dumping). Differentiating equation (2) one derives

$$\eta = -A/kI(P_o^*/P_I) \qquad (6)$$

with P_I the equilibrium pressure before dumping the beam. In practice this method ceases to work for small pressure bumps and at very low pressures due to the excessively long response time of the gauge control units. Therefore a second method is used, based on equation (5) for the equilibrium pressure. Here the knowledge of the effective pumping speed S_{eff} is required which can be obtained either from calculation, or by measurement of the dynamic pressure behaviour when the above limitation does not apply.

Most of the experimental work on beam induced gas desorption has been done in an especially equipped 10 m long straight section of the ISR. There sufficiently reproducible experimental conditions could be maintained and provisions made for various diagnostic devices. Fig. 3 shows a cross-section through the vacuum chamber with the ribbon like proton beam in the centre and an electrode which extends about 6 m along the beam direction. Depending on the electrode voltage the potential of the beam and thus the energy of the ions hitting the inner surface vacuum chamber can be varied in a controlled way. There is a beam neutralisation facility consisting of a pair of electrodes at each end of the section which can be biased so as to trap all electrons produced in the test section and thus effectively neutralising the positive space charge of the beam. This enables one to experiment at any convenient level of beam current and to vary independently the ion energy from virtually zero volts up to energies corresponding to cleared beam currents well above 20 A. Various test gases can be injected by a leak valve and the rest gas or pressure bump composition analysed. Four titanium sublimation pumps mounted on short side arms as well as two sets of "linear" sublimators stretched along the bottom of the chamber can be activated to increase the pumping speed. Samples having undergone different cleaning or surface treatments can be introduced into the bottom of the vacuum chamber.

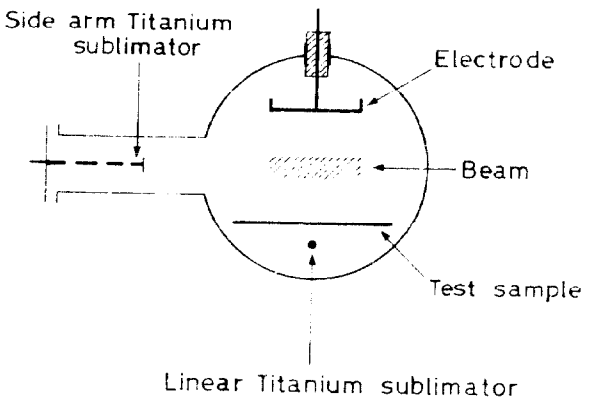

Fig. 3 Cross-section of the experimental arrangement to study ion induced gas desorption effects.

4. Results of various surface treatments

i) Bake-out

The ISR vacuum system has been designed for in-situ bake-out temperatures of up to 300° C. In the

early phase of operation, only mild 6-hour bake-outs at 200° C were made which proved to be insufficient as evidenced by the appearance of the pressure bump phenomenom at the 4 to 5 A level. The more rigorous bake to 300° C for 24 hours reduced η in the worst places by at least a factor of two and beam currents of up to 10 A could be obtained. Repeated bake-outs seem to give still further improvement but the effect is marginal. Also there are practical limits to lengthening the time to excess of 24 hours and unfortunately only at some places it is possible to increase the temperature above 300° C. Bake-outs at 340° C prove indeed to be very effective as is shown in Fig. 4, comparing η as a function of ion energy for one 300° C and a subsequent 340° C bake-out. The improvement in terms of η is about one order of magnitude. In both cases the desorbed gas species are predominantly H_2 and CO in approximately equal proportion, together giving about 80 % of the desorption total - the rest being a range of light C_1 or C_2 cracked hydrocarbons. The bombarding ion species would be the same as the residual gas composition at the start (> 90 % H_2); it would tend towards the desorbed composition for high desorption rates - e.g. the 300° C curve and E_i > 1000 eV. Even though increased temperatures pose additional problems due to higher risks of leaks the result nevertheless indicates the importance of avoiding cold spots during the bake-out and offers a possible solution for lowering the gas desorption η.

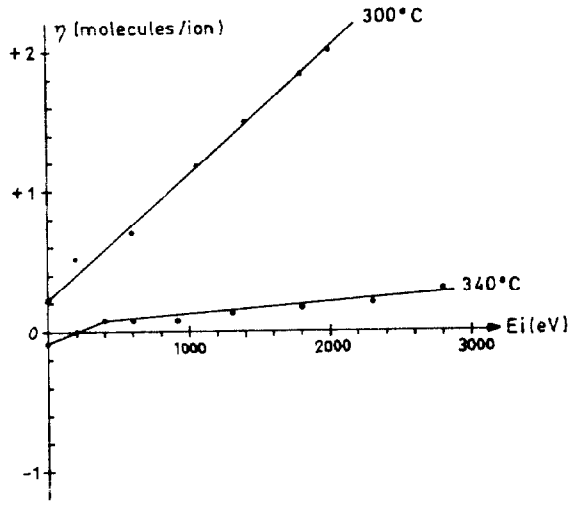

Fig.4 Desorption coefficient η as a function of the ion energy E_i for a stainless steel vacuum chamber. The curves show the relative efficiencies of 24-hour bake-outs at 300° C and 340° C. (beam current $\bar{I}$ = 3 A).

ii) Gas discharge cleaning

There exists considerable interest in investigating surface treatments other than bake-out. The latter has the disadvantage that the thermal energies at 300° C are small compared to chemical adsorption energies. A proportion of the contamination will therefore not be removed during the bake-out but can still be readily desorbed by the energetic ion bombardment of the beam.

Reducing the surface contamination by ion bombardment in a gas discharge, which simulates and accelerates the effect of the beam, has been successfully studied in the laboratory[4]. So far argon at 10^{-2} torr has been used as the discharge gas since it does not adsorb chemically on the surface and any physisorbed layer can be removed by a subsequent bake-out. The ion flux can be made very high - best results are obtained with a few 10^{18} ions cm^{-2}. The desorbed gas molecules are removed effectively by maintaining a continuous flow of the carrier gas and readsorption is reduced by operating the discharge while the chamber is hot[5]. The treatment has been made in the range of abnormal discharge to ensure bombardment of all parts of the chamber and to give reasonable treatment times - typically 10^{-4} A cm^{-2} for 3 hours. Applied voltage is normally 300 V, but bombarding ion energy will be given by the cathode-fall voltage of about 160 V.

Tests made in the ISR on chamber sections treated in-situ have shown a considerable decrease of the desorption yield - rather large negative η values (i.e. beam pumping) could even be obtained. Fig. 5 shows the desorption yield versus ion energy before and after a discharge for a stainless steel chamber and a titanium test sample. The yield after discharge treatment is negative up to high energies and apart from the initial region it is almost energy independent suggesting that the desorption term α_1 is very small. This is in clear contrast to results from a surface not subjected to the gas discharge which have always exhibited an η increasing with E_i.

The second important effect of the gas discharge is shown in Fig. 6. The steep increase of the desorption yield with beam current, irrespective of ion energy, is practically absent for the discharge cleaned surface. Curve 3 shows an example for $E_i \sim 0$. Results similar to those shown in Fig. 5 and 6 were obtained when replacing the titanium test sample by one of stainless steel.

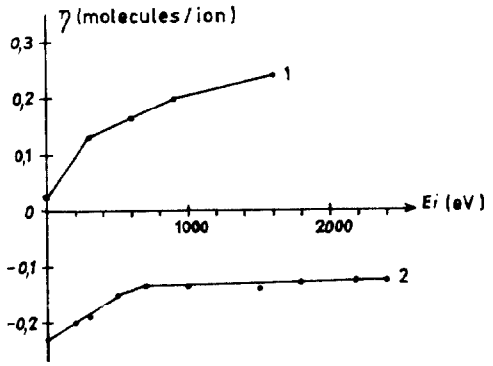

Fig. 5 The dependence of the desorption coefficient η on ion energy E_i, (1) before and (2) after an argon glow discharge treatment measured at 6 and 9,5 A respectively.

Another method of surface cleaning by ion bombardment consists in using directly the beam produced ions (beam cleaning). Experiments in this direction have so far been unsuccessful because of the low ion flux which can be obtained (about 10^{10} ion cm^{-2} sec^{-1}).

iii) Change of surface

During a gas discharge treatment as outlined above a considerable quantity of chamber material is sputter erroded and re-deposited while the gaseous desorption products are being pumped away. This sputtering will pose a problem for general in-situ discharge treatment since any insulator, unless very well protected will be covered with a conducting metal film. This problem can

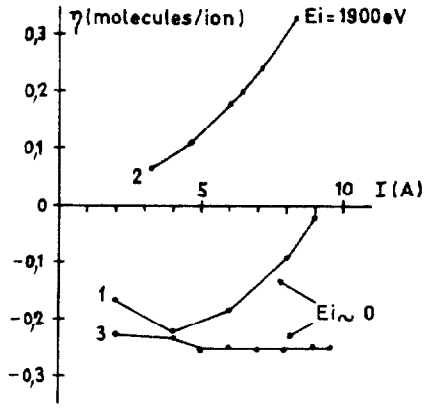

Fig. 6 The variation of the desorption coefficient η with beam intensity I (∝ bombarding ion intensity) at constant ion energy. Curves 1 and 2 are before, curve 3 after an argon glow discharge treatment.

be circumvented by a pre-treatment in the laboratory - a process which implies that the chamber is exposed to air before being installed and re-baked at 300° C in the ISR. The results, in terms of low desorption coefficient η, are similar to those obtained from the in-situ treatment - a fact which makes the pre-treatment method very attractive from the practical point of view. The explanation for this interesting result may lay in the very drastic change of surface structure.

Following the ideas developed above a layer of titanium was deposited in-situ under ultrahigh vacuum conditions from the linear sublimators. This surface, apart from pumping and giving a very low pressure in the absence of beam, showed a pronounced beam pumping effect with η = -1, i.e. complete ion absorption and no secondary desorption. Unfortunately we have not yet been able to continue measurements on a partly or fully saturated titanium layer or after exposure to air.

Conclusions

The improvement of the pumping system together with the reduction of the ion desorption yield due to improved bake-out and/or the systematic argon discharge of the chamber should make it possible to achieve stable or even decreasing pressures with the design beam intensity of 20 A. So far one does not know for how long a clean chamber will remain so and how important unavoidable small leaks will be - whether a simple rebake will be sufficient or whether a gas discharge has to be repeated from time to time. The results so far are nevertheless encouraging and the beneficial effect of the gas discharge seems to survive even several prolonged exposures to air and rebakes. The intensity dependence of η, apparently absent after the discharge cleaning may nevertheless reappear at higher current levels. However we feel confident that the combined effects of higher pumping speed, lower base pressure, higher or more uniform bake-out temperature and glow discharge treatment in sensitive regions when necessary will prove sufficient to remove vacuum limitations up to ISR currents of at least 20 amperes.

Acknowledgements

Many members of the ISR Vacuum Group have contributed to the work reported in this paper. We would like to acknowledge in particular the important contributions by E. Fischer to the basic understanding of the pressure instability, the work of A. Mathewson and A. Grillot on the applicability of the gas discharge treatment and the competent assistance of J.C. Decroux in all ultrahigh vacuum matters.

References

1) B. Angerth, E. Fischer, O. Gröbner. The Clearing Fields of the ISR. Proceedings 8th International Conf. on High Energy Accelerators, 1971, p. 238.

2) P.A. Readhead, J.P. Hobson, E.V. Kornelson. The Physical Basis of Ultrahigh Vacuum. Chapman and Hall, 1968, chapter 4.

3) G. Lewin. Fundamentals of Vacuum Science and Technology, McGraw Hill, 1963.

4) A.W. Jones, E. Jones, E.M. Williams. Investigations by Techniques of Electron Stimulated Desorption of the Merits of Glow Discharge Cleaning of the Vacuum Chamber of the ISR. CERN-ISR-VA/72-38.

5) R.S. Calder, A. Grillot, A.G. Mathewson. Electron Induced Desorption from AVESTA SKRN Stainless Steel. CERN-ISR-VA/72-34.