A METHOD TO MEASURE THE VACUUM STABILITY LIMIT OF PROTON STORAGE RINGS IN THE LABORATORY

by

D. Blechschmidt

Abstract

A simple method to determine the critical beam current in a real size vacuum system for proton storage rings is described. Argon gas is injected into the test system and ions created from it by electrons that orbit along a thin wire anode strung out over the total length of the beam pipe. They are accelerated by the same type of potential as is generated by the proton beam and driven into the beam chamber wall. The partial pressure change of individual gas components resulting from this ion bombardment is measured. Since it is directly related to the critical current and to the beam pumping speed, the vacuum behaviour of a prototype section for a storage ring may be predicted. The measurements may be carried out in the laboratory and in situ, i.e. by preserving the actual surface conditions achieved by various vacuum procedures.

Geneva, 20th August 1976
1. INTRODUCTION

Vacuum instability arising from ion-induced molecular desorption is one of the most serious limitations to the beam current in proton storage rings. This effect has been studied and fought against at the CERN Intersecting Storage Rings (ISR) for several years\textsuperscript{1)-6}. As a consequence, the critical current is now far beyond the original beam current design figure of 20 A. It was achieved by argon glow discharge cleaning\textsuperscript{2),3)} of the beam chambers prior to installation, by baking them in situ at 300-350\textdegree{} C for about 24 hours, and by adding more pumping capacity around the circumference of the ISR.

The design of a new 400 GeV colliding proton beam facility with superconducting magnets is now being studied at CERN\textsuperscript{7)-9}. For these Large Storage Rings (LSR) a minimum beam pipe aperture of 50 mm is defined by beam dynamics; it has been assumed as the design figure to date. The length of superconducting dipoles requires a minimum distance between the lumped pump stations of about 5 m. With these parameters and using the present ISR vacuum procedure\textsuperscript{5)10}, the critical current achieved in the LSR would not be safely above the design current of 7 A.

A larger beam pipe aperture would provide a higher local effective pumping speed and thus a higher critical current; however, it would also increase the construction cost considerably. New methods and probably also new materials are hence called for to achieve the required vacuum stability. The ISR may hope-fully benefit from particular cases.

Special procedures, such as in situ glow discharge cleaning, in situ sputtering of titanium and cooling the beam pipe down to liquid nitrogen or helium temperatures, have been proposed for the LSR and are being investigated. The benefits of new materials such as titanium and aluminium alloys are also being studied. It is hoped that these new methods and materials have the effect of reducing the amount of gas released by ion bombardment and also that they provide some linear pumping speed.

The positive ions are generated from the residual gas by the coasting proton beam. They are radially accelerated by the beam potential and impinge therefore on the beam pipe wall at approximately normal incidence. The ion current density is proportional to the residual gas pressure and varies with it over the length of the beam pipe. It has a maximum halfway between the lumped pump stations, where the effective pumping speed as determined by the beam pipe conductance has a minimum. The critical current is thus governed by the local effective pumping speed at the centre of a magnet, and the vacuum instability is initiated there
before it spreads out towards the pump stations.

Measurements of critical current should therefore be carried out in a real size system — which is not simply defined by the vacuum pipe conductance — in order to take account of all possible geometrical effects, some of which are even not yet understood. Furthermore it is obvious that they have to be done in situ to preserve the actual surface conditions defined by the molecular sticking and ion-induced desorption coefficients.

The critical current in the ISR is usually predicted from the ion-induced molecular desorption coefficient \( n_L \). This parameter is measured in the laboratory\(^{11,12}\) using an ion beam source and small samples of various materials subjected to different surface treatment procedures. Observations at the ISR \(^{13,14}\) confirmed these predictions. The theory, however, on the basis of which they have been made, takes the surface cleanliness into account only, but neglects its active role as far as re-adsorption is concerned\(^5\). This procedure is therefore, because of the difference in geometry, not suitable for predicting the LSR vacuum limit, even though it is a good means for in-situ surface studies.

Thermal sources of lithium or potassium ions\(^{13}\) are more promising because of their large emittance, but are still unsatisfactory in view of the real process of ion generation and acceleration in a proton storage ring. The most realistic conditions are of course found in the ISR. The requirement that these investigations have to be compatible with normal machine operation implies considerable inconvenience and even various restrictions. Larger series of measurements are necessary to gain some statistical confidence, but it is not easy to carry them out within a reasonable time. It is finally most desirable to determine the critical current in a vacuum system of actual LSR dimensions to avoid scaling. This is impossible in the ISR, where the proton beam cannot be accommodated in a circular pipe of only 50 mm aperture.

For two of the possible vacuum procedures — glow discharge cleaning and in-situ sputtering of titanium — a thin wire stretched out along the beam axis\(^1b\) is required. Mounting a small electron source in addition to this wire halfway between the pump stations is all that is needed to obtain a powerful means for surface investigation without changing any of the basic vacuum system characteristics. Electrons provided by this source spiral around the central wire which is at positive potential and travel down along the beam pipe. Similarly to the working principle of an orbitron, they create, from the residual gas, ions which are accelerated in the radial electrical field between the wire and the wall just as in a real machine. The ion current distribution is approximately the
same in the laboratory system as in the proton storage ring.

2. EXPERIMENTAL

The basic set-up of the vacuum system which is used to measure critical currents resulting from various surface pre-treatments is shown in Fig. 1. Its dimensions correspond to that of the most critical part of the LSR vacuum system, i.e. a long superconducting dipole section with a 5 m long beam pipe of 50 mm diameter. The lumped pump speeds, provided by a sputter ion pump and a titanium sublimation pump at either end, are large compared with the beam pipe conductance.

An injection valve is mounted at the pump station at one end and a turbo-molecular pump which may be valved off is connected to the other. The residual pressure is monitored by three small extractor type ionization gauges, one at each end of the pipe, close to the pumps, and one halfway between them. The gauges have a useful range from about $5 \times 10^{-4}$ to $5 \times 10^{-12}$ torr.

At the centre of the system, a small thorium-coated tungsten filament is mounted within the beam pipe. Electrons emitted by this cathode are accelerated towards the anode, a titanium wire of 1 mm diameter that is strung out along the entire length of the pipe. A small electrostatic reflector prevents the electrons from being collected immediately. A quadrupole mass spectrometer is mounted close to the electron source and may be shut off from the system by a valve.

The vacuum test system is all metal. It can be baked up to 350°C using resistive heating for the pipe and heater jackets for the rest. A base pressure of less than $1 \times 10^{-11}$ torr at the ends and less than $5 \times 10^{-11}$ torr at the middle of the pipe is typically achieved after a 24-hour bake at 300°C.

A separate small vacuum system is used to purify and to store argon gas. It is injected into the main system at high pressure to provide sufficient ions to bombard the beam pipe wall. The purification system is essentially a large sublimation pump. It is baked and evacuated to below $10^{-4}$ torr before filling in argon (99.99% clean) up to atmospheric pressure. A few sublimations yield sufficient pumping speed to reduce impurities with non-negligible sticking coefficients to a metal surface, such as H₂, CO, CO₂ etc. The purified argon is kept stored at atmospheric pressure.
3. MEASUREMENT PRINCIPLE

The critical current is the upper limit to the intensity of coasting proton beams beyond which the residual gas pressure rises continuously. It may be defined for any residual gas component; in this case the lowest value of "individual critical currents", \( c_{\text{i}} \), defines the vacuum stability limit. In what follows, we shall refer to individual critical currents only. They are directly related to the change of the corresponding partial pressures when ions impinge at the beam pipe wall with a given current density. In the laboratory these ions are created by orbiting electrons ionizing molecules of injected argon. By maintaining the argon pressure high enough so that each electron creates one argon ion, we may eliminate the proportionality of the ion current to the argon pressure. This is convenient since the latter decreases during a measurement. The partial pressure change of various residual gas components, measured as a function of the electron emission current, yields therefore the critical current directly.

Although the critical current is influenced by many parameters such as the molecular desorption coefficient, the sticking factor, the vacuum conductance, etc., we do not have to measure each of them individually. If certain provisions are made, which are explained below, these parameters determine the pressure rise per unit electron emission current globally in a similar way as in a real machine. In the laboratory, the rise is inversely proportional to the critical current that we would observe if the test system were part of a real machine with a beam stacked in it.

Gas components with negative net ion-induced molecular desorption are pumped by the proton beam; critical currents are therefore meaningless. In the laboratory, the same components are pumped by an almost equal mechanism. The net desorption and thus the effective beam pumping speed may be obtained for the LSR from the rate of pressure decrease as a function of electron emission.

The choice of argon was motivated not only by its being the cheapest rare gas but also by its mass \((m = 40)\) being only little less than that of \( \text{CO}_2 \) \((m = 44)\), which is the highest mass of all gas components prevailing, in an all-metal system. Since the desorption coefficient increases with the mass of the incident ion\(^{12}\), critical currents obtained with argon ions are pessimistic rather than too high.

The possibility of using the actual residual gas at base pressure for ion creation, as is the case in a real machine, has also been considered. This would provide an attractive method of observing pressure bumps in the laboratory.
However, it is easy to show that we would require for an electron emission current of

\[ I \geq \frac{\sigma_M}{\sigma_L} \cdot I_p \approx 10^{-2} I_p \]  (1)

where \( \sigma_M \) (machine) and \( \sigma_L \) (lab.) denote the ionization cross-sections for a high-energy proton beam (\( \geq 10 \text{ GeV} \)) and for low energy electrons (100-500 eV), respectively, to achieve the same effect as a stacked beam of intensity \( I_p \). For a beam current of only \( I_p = 1 \text{ A} \), an electron emission current of 10 mA would be necessary. This is not only beyond the space charge limit of the particular electron source used\(^{18}\), but it would also drastically increase the electron impact molecular desorption.

4. PREREQUISITES OF MEASUREMENTS

The interpretation of measurements is difficult in terms of critical currents, unless certain prerequisites are satisfied:

(i) The pressure increase due to electron impact desorption and thermal outgassing from the anode wire should be negligible compared with the residual partial pressure of the corresponding individual gas component at zero electron emission. This condition can be achieved by resistive heating of the anode wire at \( \approx 400^\circ \text{C} \) for 20 hours, followed by electron bombardment at 500 eV with a total dose of \( \approx 5 \times 10^{16} \) electrons/cm\(^2\). The total spurious pressure increase after this treatment is typically less than \( 5 \times 10^{-12} \) torr N\(_2\)-equiv., for the maximum electron emission of 2 mA. Partial gas pressures during critical current measurements are typically two orders of magnitude higher.

(ii) All impurities injected together with the argon gas should have a negligible effect on the surface state of the pipe, which was prevailing prior to the injection. With the argon cleaned in the purification system, gas injection into the system (at a base pressure of about \( 3 \times 10^{-11} \) torr at the centre) can be made for 15 min at 1 torr and thereafter pumped down to below \( 5 \times 10^{-11} \) torr within the same time. The total amount of impurities injected, mainly methane, is typically less than 500 ppm of the injected argon pressure.

(iii) The pressure of the injected argon should be high enough for each orbiting electron to create one argon ion. The ion current \( I^+ \) to the tube wall,
created for any particular gas component at pressure \( p \) is given by the well-known relation

\[
I^+ = IKp
\]  
(2)

where \( I \) denotes the electron emission and \( K \) a sensitivity factor. Equ. (2) is valid as long as:

\[
p << p^* = 1/K
\]  
(3)

i.e. in a range where the electron mean free path is determined by the geometry of the set-up. Only for

\[
p > p^* \text{ do we have } I^+ = I
\]  
(4)

defining the range where the electron path is ended by an ionizing collision with a residual gas molecule. In order to be able to specify the pressure working range for the injected argon

\[
P_{Ar} > P^*_{Ar} = 1/K_{Ar}, \text{ i.e. } I^+_{Ar} = I
\]  
(5)

so that equ. (4) is satisfied, we have to measure \( P^*_{Ar} \). Injecting argon up to the maximum pressure that is compatible with operation of the mass spectrometer and the gauges, about \( 5 \times 10^{-4} \text{ torr} \), and tuning the spectrometer to a mass number of a gas with positive desorption coefficient such as \( m = 28 \) (CO), we obtain a signal \( I_{CO} \). It is proportional to the argon ion current \( I^+_{Ar} \) at fixed electron emission current. Plotting \( I_{CO} \) as a function of \( P^*_{Ar} \), we obtain the curve shown in Figure 2. The threshold pressure \( P^*_{Ar} \) is found from the kink. For the LSR test system, \( P^*_{Ar} = 8 \times 10^{-5} \text{ torr} \), which leaves a good working range for argon pressures at about 1-4 \( \times 10^{-5} \text{ torr} \).

(iv) The electron mean free path \( \lambda \), should be long with respect to half the total beam pipe length \( L \) in the pressure range where it is only limited by geometrical imperfections:

\[
\lambda > L \text{ for } p << p^*
\]  
(6)

otherwise a smaller quantity of electrons would be available nearer to the ends of the
beam pipe than at the centre in the working range defined by equ. (5). This would give rise to an underestimation of the stability limit, because the ion current density would be too high in the middle of the tube, where partial pressures are measured.

At low pressures, i.e. as long as equ. (2) holds, the sensitivity is related to the mean free path:

$$K = \lambda \sigma_L \gamma$$

where $\sigma_L$ denotes the average electron impact ionization cross-section over the range of kinetic energies of the electron on its way to the anode and $\gamma = 3.22 \times 10^{16}$ molecules/cm$^3$·torr at 300 K. At high pressures, $p > p^*$, the mean free path is dependent on the gas species, and we may estimate it from

$$\lambda = 1/\sigma_L \gamma p^* > 1.4 \times 10^{-3} \text{ cm}$$

where $\sigma_L = \sigma_{Ar} < 2.6 \times 10^{-16}$ cm$^2$\textsuperscript{20}, i.e. the sensitivity of the orbitron-like arrangement is high enough to satisfy equ. (5), since $L = 250$ cm.

The high sensitivity is achieved by the choice of the radial cathode filament position $r_c$, yielding the largest domain for injection onto stable orbits\textsuperscript{21}:

$$r_c = 0.607 \cdot r$$

and by its potential with respect to the grounded tube

$$U_c = U_a / 2 \ln(2r/d)$$

with $r$ the beam pipe radius and $d$ the anode wire diameter. Its potential $U_a = 550$ V was chosen so as to minimize electron impact desorption from the anode, secondary electron emission from the beam pipe and the Townsend discharges but also in order to stay below the space charge limit of the emission current and to have a sufficiently high argon ion energy.

The use of a small reflector electrode prevents electrons from falling directly to the anode. With the test pipe cooled to liquid nitrogen temperature (which was done during vacuum stability measurements for a
"cool-bore" design), a faint luminous glow could be observed that spread out along the entire length of the beam pipe. This confirms that equ. (6) is in fact fulfilled. It is not clear why this phenomenon is absent with the pipe at room temperature.

(v) Finally, measurements should be carried out in a single gas system, to avoid having primary ions of different gas species. Only under this condition can we use a simple expression for the critical current which would be of doubtful value in a mixed gas system. Hence we stipulate that

$$P_{Ar} \gg P$$

(11)

for all residual partial gas pressures $P$, at any time of measurement. Unless the ion induced molecular desorption is exceedingly high, we always have

$$P_{Ar} > P_{Ar}^* \gg P$$

(12)

equ. (11) therefore being satisfied with condition (5).

It is obvious that critical current measurements require the same lumped pumping speed as in a real machine for at least those residual gas components with positive net ion desorption. Thus, sublimation pumps will have to be well activated during measurements to maintain a pumping speed that is large compared with the beam pipe conductance. The use of mechanical pumps was rejected because they are a possible source of hydrocarbon contamination. Sputter ion pumps are of course switched off during the measurement in order to keep the pumping speed for Ar as small as possible.

Injecting and pumping argon at a fixed rate to maintain a constant pressure is not desirable because gas impurities injected together with the argon may be accumulated at the surface. Another effect would be the argon pressure gradient, i.e. an ion current density distribution, which is different from that in a real machine.

5. INTERPRETATION OF MEASUREMENTS

A. The Critical Current

Different models have so far been proposed to describe the pressure bump
mechanism in a proton storage ring. The expression for the critical current \( I_c \) is nevertheless the same, and given by:

\[
I_c = \frac{e}{\eta M} \left\{ \frac{W}{4} s_m \bar{V} + A \frac{\omega}{L} + c \left( \frac{\omega}{L} \right)^2 \right\}. \tag{13}
\]

In this expression, \( \eta M \) denotes the net ion-induced molecular desorption coefficient (which is the relevant one for a machine), \( s_m \) is the molecular sticking factor, \( \bar{V} \) the average velocity of a molecule in the gas phase and \( \tau_m \) its average sojourn time in an adsorption state at the surface. The parameters \( W, A \) and \( c \) are the perimeter, the aperture cross-section area and the vacuum conductance per unit length of the beam pipe, respectively. The first root of the transcendental equation

\[
\omega \tan \omega = S_L L/c \quad \tag{14}
\]

yields \( \omega \) for a given lumped pump speed \( S_L \).

For further discussions it is convenient to rewrite eqn. (13) using the following substitutions:

\[
\tau_V = \frac{4A/Ws_m \bar{V}}{} \quad \tag{15}
\]

and

\[
\tau_o = \frac{AL^2/c\omega^2}{;} \quad \tag{16}
\]

\( \tau_V \) may be interpreted as the sojourn time of a molecule in the gas phase, for zero lumped pump speed. The other parameter, \( \tau_o \) is the pump-down time constant with lumped pumping only, i.e. the sojourn time of a molecule in the gas phase for zero linear pump speed. Hence

\[
I_c = \frac{eA}{\eta M c} \left\{ \frac{1}{\tau_V} + \frac{1}{\tau_m} + \frac{1}{\tau_o} \right\}. \tag{17}
\]

Provided that \( S_L \) is not too small, \( \tau_o \) is approximately.\)
\[ \tau_0 \approx \frac{4AL^2}{c^2} \left( 1 + \frac{c}{LS} \right)^2 \]  

(18)

demonstrating that the pump-down time may increase considerably if \( S \) is not large compared with the beam pipe conductance.

For the ISR, \( \tau_v, \tau_m \to \infty \) is usually assumed. With \( S \gg c/L \), we have

\[ \eta_M^{\infty} = \frac{\varepsilon n^2 c}{4 \sigma_M L^2} \]  

(19)

This relation \(^5\) is used to predict the vacuum limit for the ISR, once \( \tau_M \) is obtained from laboratory measurements. These predictions agree well with the observed stability limit.

A result of the present model \(^2^2,^2^3\) is that pressure bumps decay with a time constant governed by the molecular sojourn time \( \tau_m \). The dynamic behaviour of pressure bumps in the ISR indicates that \( \tau_m \) is very long, at least of the order of hours, for gas components relevant in the context of critical currents. The assumption of sojourn times of less than a few seconds would also be in contradiction to the fact that gas is adsorbed in non-negligible quantities. On the other hand \( \tau_0 \) is typically less than 1 s for conductance-limited lumped pumping within a wide range of parameters \( r \) and \( L \). Hence we may rewrite (17) with \( \tau_0 \ll \tau_m \) for the critical current of the test system:

\[ I_C = \frac{eA}{\eta_M^{\infty}} \left( \frac{1}{\tau_v} + \frac{1}{\tau_0} \right) \]  

(20)

Further, reducing equ. (20) to equ. (19) is equivalent to neglecting the active role of the surface. The assumption of an infinite sojourn time \( \tau_m \), however, yields only a little more pessimistic critical currents. Equ. (20) is therefore also useful for more volatile gas components such as Ar or \( \text{CH}_4 \), characterized by short sojourn times.

B. The Desorption Coefficient

The ion-induced molecular desorption constant is defined with the following relation:

\[ N_k = \sum_j \left\{ \eta_{jk} - (s_i)^e j^* \delta_{jk} \right\} N^+_j; \quad j = 1 \ldots j_{\max} \]  

(21)
where \( N_k \) is the net change of the number of molecules of species \( k \), due to the bombardment of the wall by \( N_j^+ \) ions of up to \( j_{\text{max}} \) different species \( j \). The probability of desorbing a molecule of type \( k \) by an ion of type \( j \) is denoted by \( \eta_{jk} \); \( s_{ij} \) is the probability of an ion of species \( j \) remaining permanently trapped in the beam pipe wall after impact.

In the laboratory, the incident ions are of one single species only and this is not present before the measurement is initiated. If we denote this species with \( j \neq k \), the molecular desorption coefficient measured in the laboratory is

\[
\eta_L = (\eta_L)_k = \frac{N_k}{N_j^+},
\]

(22)

if, for convenience, we omit the index \( k \), denoting the kind of desorbed species. In a storage ring, however, the ions are produced from the actual gas mixture. There the net desorption coefficient is

\[
\eta_M = (\eta_M)_k = \bar{\eta}_L - a s_i
\]

(23)

with the fraction

\[
a = a_k = \frac{N_k^+}{\sum_j N_j^+}
\]

and the average laboratory desorption coefficient

\[
\bar{\eta}_L = \bar{(\eta_L)}_k = \sum_j \eta_{jk} \frac{N_j^+}{\sum_j N_j^+}.
\]

Recent studies have shown that \( \eta_L \) is rising with increasing mass of the bombarding ion \(^{12}\). Since, however, the difference is already almost negligible for \( m = 40 \) (Ar) and \( m = 44 \) (CO\(_2\)), which are the highest apparent mass numbers observed in a typical residual gas spectrum for a clean metal system, using argon ions, we have

\[
\eta_L \gtrsim \bar{\eta}_L \gtrsim 0
\]

(24)

and therefore

\[
\eta_L \gtrsim \eta_M + a s_i \gtrsim 0
\]

(25)
C. The Vacuum Equation

The vacuum equation \(^{24}\) in the test system is similar to the expression deduced for the machine \(^5\) and for \(\tau_m \to 0\):

\[
A\dot{p}(x,t) = Wq + \frac{1}{2LeY} \left\{ \eta_L^I_{x,k} + \eta_M^I_{x,k} \right\} - \frac{W}{4} \frac{\partial x}{\partial m} \nabla p + cp''(x,t)
\]  

(26)

The specific thermal outgassing constant is given by \(q\). The dot and the double prime denote the usual first and second derivative of the partial pressure \(p(x,t)\) with respect to time and position along tube.

The general solution of eqn. (26) is a strongly converging Fourier series. Neglecting all but its first term, we get a solution for the pressure halfway between the lumped pumps, i.e. at the mass spectrometer position \(x = 0\), which is only time dependent. It may be rewritten in integral form. Substituting equations (2), (5), (15), (16) and (20) we obtain

\[
A\dot{p} = Wq + \frac{I}{2LeY} \left\{ \eta_L + \eta_M K^P \right\} - \frac{\sigma_M^e}{e} \eta_M I_{c} P.
\]  

(27)

This equation relates the critical current in the test system and the pressure response to various electron emission currents.

D. Relation for the critical current

For all those gas components participating in pressure bumps, we have \(\eta_M > 0\), the critical current may thus be derived from eqn. (27). We will disregard Ar at this stage. Since \(K_{Ar^*}\) is of the same order of magnitude as \(K\), we find from eqns. (5), (11) and (25):

\[
\eta_L = \eta_L^{K^*} K_{Ar} \gg \eta_L K^P \gg \eta_M K^P.
\]  

(28)

Making use of eqn. (28) and integrating eqn. (27) gives

\[
p(t) = p(0) + \frac{\eta_L (I - I_o)}{2L\eta_M \sigma_M I_c} \left[ 1 - \exp \left\{ - \frac{\sigma_M \eta_M I_c}{eA} t \right\} \right]
\]  

(29)

describing the partial pressure response when the emission is switched from \(I_o\)
to I at $t = 0$. The exponent is negative, therefore a new equilibrium pressure will be reached. The parameter

$$
\xi = \lim_{t \to \infty} \frac{p(t) - p(0)}{I - I_0}
$$

can be measured, and making use of relation (25) again we have

$$
I_c = \frac{1}{2Lq\sigma_{\gamma}} \cdot \frac{\eta_L}{\eta_M} \geq \frac{1}{2Lq\sigma_{\gamma}}
$$

(30)

From the initial pressure rise per time unit $\dot{p}(0)$, switching the electron emission from $I_0$ to I, $\eta_L$ may also be determined:

$$
\eta_L = e\gamma V \frac{\dot{p}(0)}{I - I_0}
$$

(31)

where $V = 2LA$ denotes the tube volume. The second relation is unfortunately only useful in the case of very small $\eta_L$ values, because it is difficult to measure $\dot{p}(0)$ with sufficient accuracy.

E. Relations for beam pumping

Gas components that are pumped by the proton beams are characterised by $\eta_M < 0$. Again we will disregard Ar. In the laboratory system we still have a pressure rise if

$$
\eta_L > |\eta_M| \frac{p}{p_{Ar}}
$$

(32)

Equ. (30) no longer makes sense because it would yield negative critical currents. However, $|\eta_M| < 1$; hence $\eta_L$ is small and equ. (31) can therefore be used to determine $\eta_L$ with good accuracy. An upper limit to $\eta_M$ is then obtained from equ. (32). It is important to note that any gas component for which a pressure decrease is observed while the electron emission current is being increased, is characterized by $\eta_M < 0$; it is therefore irrelevant for vacuum stability. A pressure increase, however, does not exclude that this component could possibly be pumped by the beam.

In the case of a pressure decrease due to higher electron emission, more
molecules of this particular component are ionized and permanently implanted in the wall, than are desorbed, i.e.

$$\eta_L \ll |\eta_M| \frac{p}{P_{Ar}} \cdot \frac{\sigma}{\sigma_{Ar}} \approx |\eta_M| \frac{p}{P_{Ar}}$$

(33)

In the extreme case, we may neglect $\eta_L$ completely and integrate equ. (27):

$$p(t) = \frac{a}{b} + (p_0 - \frac{a}{b}) e^{-bt}$$

(34)

with

$$a = \frac{W}{A} q \quad \text{and} \quad b = \frac{1}{\tau_v} + \frac{1}{\tau_0} - \frac{I}{e \gamma V} K_n_M$$

(35)

In most practical cases (but excepting strong linear pumping)

$$b \approx \frac{-I}{e \gamma V} K_n_M$$

(36)

because $s_m$ and $S_A$ are small for gas components for which $\eta_L$ is negligible. Defining

$$S = -\eta_M K / e \gamma$$

(37)

we obtain from equ. (34)

$$p(t) = \frac{Q}{SI} \left[ 1 - \exp \left( -\frac{SI}{V} t \right) \right] + p_0 \exp \left( -\frac{SI}{V} t \right)$$

(38)

where $Q$ denotes the total outgassing rate of the system. There will be a final equilibrium, if $Q$ is not too small. Experimental observations agree with equ. (38) for components with $\eta_L \approx 0$.

The orbitron pumping speed $S$ may be estimated from:

$$S_\infty = \lim_{t \to \infty} \frac{Q}{Ip(t)}$$

(39)
However, a long time after the end of bombardment the pressure is still increasing, indicating either that many ions are neutralised in the bulk and diffuse back into the gas phase, or that ion bombardment enhances the outgassing rate \( 30 \). The total outgassing rate \( Q \) is therefore a function of \( I \), and it is difficult in most cases to determine \( S \) from equ. (39).

In analogy to equ. (31), we obtain from equ. (38) and (39)

\[
S = -\frac{V}{I} \frac{\dot{p}(0)}{\Delta p}
\]

with \( \Delta p = \lim_{t \to \infty} [p_o - p(t)] \), so

\[
\eta_M \approx \frac{e \gamma}{kT} \frac{\dot{p}(0)}{\Delta p}
\]

which can be used to estimate the linear beam pumping speed in a machine:

\[
S_{\text{lin}} = |\eta_M| \frac{c}{e}
\]

F. Argon

Since argon is injected into the system, it is a special case. Rewriting equ. (27) for argon gives

\[
\dot{p} = \frac{p_o}{W} \left( 1 + \frac{\eta_M}{2 \nu e \gamma} \right)
\]

because the lumped and linear pumping speeds are negligible compared with the speed resulting from ionization by orbiting electrons. Integration gives

\[
p(t) = p_o + \left( \frac{Q}{V} + \frac{\eta_M}{V e \gamma} \right) t
\]

Again, we cannot neglect \( Q \), which is probably due to back-travelling of temporarily trapped argon. However, \( Q \) is negligible in a virgin tube. Therefore we have, with equ. (25), for \( \alpha = 1 \) and \( \eta_L = 0 \):

\[
S_{i,Ar} = -\nu e \gamma \frac{\ddot{p}(0)}{I}
\]

and

\[
S_{\text{lin},Ar} = -\nu e \gamma \frac{\dot{p}(0)}{M}
\]
It was found that this relation could be used for argon doses of less than about $10^{15}$ ions/cm$^2$. In the LSR test system, this corresponds to 20 min bombardment at 1 mA electron emission current. This dose is approximately the limit beyond which the surface is being cleaned by the ion bombardment and should therefore not be exceeded anyway. In a machine, this dose will certainly never be reached. In the LSR almost 40 years of continuous operation at maximum current would be required to obtain it.

G. Pressure response time constants

Equ. (29) describes the dynamic behaviour of the partial pressure, for gas components with $\eta_M > 0$. The time constant, obtained from equ. (20)

$$\tau = \frac{1}{\left(\frac{1}{\tau_N} + \frac{1}{\tau_0}\right)} < \tau_0$$  \hspace{1cm} (47)

is expected to be very short, typically less than 1 s. However, the time needed to establish new pressure equilibrium was often of the order of several minutes.

A possible explanation would be that the partial pressure rises so high during the bombardment that condition (11) is no longer fulfilled. Inspecting equ. (27) we also find the time constant for this case:

$$\tau' = \left[\frac{\eta_M}{e\lambda} \left\{\sigma_{M} T_{C} - \frac{KI}{2LY}\right\}\right]^{-1}$$  \hspace{1cm} (48)

which is related to $\tau$

$$\tau' = \frac{\tau}{1 - \frac{KI}{2LY\sigma_{M} T_{C}}}.$$  \hspace{1cm} (49)

Fig. 3 is a plot of the ratio $\tau'/\tau$, assuming $K = 1/p_{Ar} = 1.25 \times 10^4$ torr$^{-1}$, $L = 250$ cm and $\sigma_{M} = 1.5 \times 10^{-18}$ cm$^2$. It shows that in fact the time constant $\tau'$ for this feedback type desorption - which acts formally like a negative pumping speed - increases steeply as the emission current approaches

$$I \rightarrow I^* = 2LY\sigma_{M} p^* I_{C}$$  \hspace{1cm} (50)

and we may even expect a pressure bump in the test system for $I = I^*$. 
Experimental observation, however, contradicts this explanation. In order to explain a response time constant of at least 10 s, we would require $I = 0.9 \cdot I^*$, for example. Any further increase of $I$ should cause a very steep and non-linear pressure rise; such an observation could never be made.

When switching on the ion bombardment, slow pressure changes have been measured in the test system on many occasions. Similar behaviour is also found in the ISR in the presence of high intensity beams. Since a single gas model cannot explain this effect without inconsistencies, it was recently extended to a two-gas mixture, $H_2$ and CO, and the results for reasonable vacuum parameters were found to be consistent with experimental evidence. In the test system, however, long-term pressure rises have also been observed under conditions which exclude the application of a mixed gas system, i.e. even when equ. (11) was fulfilled. Furthermore, strongly enhanced and slowly decaying outgassing rates have been observed after an in situ glow discharge in the system, particularly for CO. This also confirms an earlier observation.

The mechanism responsible for this effect is not yet quite clear. It seems, however, that ion bombardment opens a source of more volatile gas within the bulk. A possible picture would be that the incident ions impart some of their energy to molecules in more tightly bound states, either at grain boundaries or lattice defects. These molecules are thus activated and they may reach the surface in a random walk if they are not retrapped. Their rate of activation is proportional to the incident ion current whereas the depletion of mobile subsurface gas is characterized by an exponential decay. This can formally be described by

$$q = -\frac{1}{\tau_b} \left[ q(t) + \eta_b \frac{1}{2 W L e_y} \right] \quad (51)$$

where $\eta_b$ is the probability that an impinging ion produces a molecule "below" the surface or within the bulk and that this molecule arrives in the gas phase after time $\tau_b$. Integration gives

$$q(t) = q_o + \frac{\eta_b}{2 W L e_y} \left( I^+ - I_o^+ \right) \cdot (1 - \exp \left\{ -t/\tau_b \right\}) \quad (52)$$

Substituting in equ. (27) and using equ. (4), we obtain by integration analogous to the way that equ. (29) was obtained:

$$p(t) = p(t) \bigg|_{\eta_b=0} + f(t) \quad (53)$$
with

\[ f(t) = \frac{\eta_b (I-I_o) \tau}{2 L \tau_b (\tau - \tau_b) / \tau_b - \tau e^{-t/\tau}} \]  

(54)

Fig. 4 is a plot of equ. (52) using the following parameters: \( \tau = 0.4 \) s, \( \tau_b = 20 \) s, \( \eta_b = 3 \cdot 10^{-4} \), \( \eta_L = 0.02 \), \( I = 1 \) mA, \( L = 250 \) cm and \( p_o = 1 \cdot 10^{-7} \) torr. These parameters are realistic and curves similar to the result are usually observed in the test system.

From this it follows that the enhanced outgassing might be an effect analogous to surface desorption, i.e. an additional feedback effect exists, giving rise to a long-term vacuum instability. An investigation is beyond the scope of this work but will nevertheless be carried out. As long as ion-induced surface desorption dominates ion bombardment enhanced outgassing, i.e. \( \eta_L >> \eta_b \), we may be confident that critical currents are given by equ. (30).

The steplike pressure response a few seconds after the current has been changed can then be used to obtain the critical current. In principle, however, the equilibrium pressure should be taken, since the effect of \( \eta_L \) and \( \eta_b \) is cumulative: this will be shown elsewhere.

H. Correction for Ion Energy

The ion-induced desorption coefficient \( \eta_L \) depends on the ion energy \( E_i \). It increases with \( E_i \) but saturates at about 5 keV\textsuperscript{11,12}. In a proton storage ring, the ions are created within the beam, whose potential varies linearly with the intensity\textsuperscript{26}. For the LSR, the ion energy at maximum design current (7 A) is about 1.3 keV.

In the laboratory test system, however, the ions are created at any radial position. Their energy distribution is proportional to the electron impact ionization cross-section \( \sigma_L \), but offset in energy by the filament potential \( U_c \):

\[ N_{Ar}^+ (E_i) = \sigma_L (E_e) \]  

(55)

with \( E_e = E_i - eU_c \). \( U_c \) is given by equ. (10). The average kinetic energy \( \langle E_e \rangle \), at which an electron ionizes, is about 150 eV for an anode to cathode potential of 500 V\textsuperscript{20}. Little can be gained by further increasing the anode
potential, because the cross-section decreases for higher electron energies. The corresponding ion energy, \( E_i = <E_e> + eU_c \approx 200 \text{ eV} \) is then practically fixed, because \( U_c \) is determined by the anode potential. Various reasons have already been given above (chapter 4, paragraph iv) to keep \( U_a \) low.

Critical currents, obtained from equ. (30) have therefore to be corrected for ion energy. The correction factor with which \( I_c \) has to be multiplied is
\[
\eta_L(0.2 \text{ keV})/\eta_L(1.3 \text{ keV})
\]
It is not less than 0.15 for most gas components and surface conditions. A similar argument applies, of course, to gas components with \( \eta_w \leq 0 \).

6. EXAMPLE

The gain in critical current due to in situ glow discharge cleaning has been studied in various test pipes and for different materials. As a typical example, results obtained from a stainless steel tube (304L) will be discussed.

The test tube was cleaned following normal ISR cleaning procedures for UHV components, but it was not heat-treated. After installation, it was baked for 24 hours at 300°C. The critical currents were then measured before and after a glow discharge at 10⁻² torr pure argon, at a total dose of about \( 5 \times 10^{17} \text{ ions/cm}^2 \) and with the pipe at 300°C. This temperature was maintained some 20 hours after the discharge, to remove the implanted argon. A summary of the measurements is given in Table I.

Residual partial base pressures have increased for almost every gas component either due to the glow discharge or during a measurement, which is also some kind of ion bombardment. The exceptions are \( m = 18 \) (H₂O) and \( m = 26 \) (probably C₂H₂), the partial pressure of which either changed very little or became negligibly small. This is consistent with the picture of ion bombardment enhanced desorption.

All prerequisites explained in chapter 4 were fulfilled during the measurements. The highest partial pressure observed was CO at \( I = 1 \text{ mA} \) electron emission before the glow discharge cleaning. It was inferior to 3% of the argon pressure. For \( m = 2 \) (H₂), \( m = 12 \) (C), \( m = 26 \) (C₂H₂), \( m = 28 \) (CO) and \( m = 44 \) (CO₂), there was always a pressure increase. Fig. 5 shows the partial pressure increase as a function of the electron emission measured for H₂, CO and CO₂ before the in situ glow discharge. It can be seen that \( p \) rises proportionally to \( I \) as expected from equ. (29) over a wide range. The deviation at higher emission is explained to be due to the cleaning effect of the bombarding
ions. At the end of a measurement the partial pressure was typically higher than initially due to the increased outgassing. The arrows indicate the measurement cycle.

From these curves, $\xi$ was taken and $I_c$, corrected for 7 A beam current, calculated from equ. (30). Of course, critical currents are too pessimistic for $I_c < 7$ A and too optimistic for $7$ A $< I_c \leq 25$ A, i.e. in a range where $\eta_L$ is below the top value.

A negative pressure response was observed for $m = 16$ (CH$_4$), $m = 18$ (H$_2$O) and $m = 20, 36, 38$ and $40$ (Ar). It took a long time for the pressure to settle at a new equilibrium; $\eta_M$ and $S_{lin}$ have therefore been obtained from equations (41) and (42) for CH$_4$ and H$_2$O. For Ar, the ion sticking probabilities $s_i \approx 10^{-2}$, given by equ. (45) agree quite well with Kornelson's data measured for tungsten at 150 eV$^{28}$. The linear pumping speed $S_{lin}$ provided by the beam is extremely poor, which makes sputter ion pumps unalienable.

The last column of Table I contains $\eta_M$ values obtained from equ. (19) using the measured $I_c$ values. One would have arrived at these figures had these critical currents been observed in a machine. For a chamber without glow discharge cleaning they correspond to those generally accepted for the ISR for a chamber that had been baked only$^{29}$. In situ glow discharge cleaning results in an improvement of critical currents by a factor of about ten.

7. ACKNOWLEDGEMENTS

The stimulating discussions with H. Halama, (Brookhaven Nat. Lab.), J.P. Hobson (Nat. Res. Council, Canada) during the early stage of this work and valuable comments given by R. Calder and E. Fischer (CERN) are gratefully acknowledged. The author would also like to thank C. Grünhagel and A. Jones for technical assistance.
REFERENCES

7) K. Johnsen, CERN/ISR-GS/75-14, 1975.
10) D. Blechschmidt, CERN/ISR-VA/75-29, 1975.
12) N. Hilleret, private communication - to be published.
20) L.J. Kiefer and G.H. Dunn, Rev. Mod. Phys. 38, 1 (1966) and references given therein.
22) O. Gröbner, private communication - to be published.
31) D. Blechschmidt, report to be published.
FIGURE CAPTIONS

Fig. 1 Sketch of the vacuum test system used to measure critical currents. (SU = sublimation pump, SP = sputter-ion pump, TM = turbomolecular pump, QMA = quadrupole mass analyser, EG = extractor ionisation gauge, IV = injection valve, BP = backing pump, ES = electron source, R = reflector).

Fig. 2 Plot of the mass spectrometer signal for mass 28 versus the Ar partial pressure at fixed electron emission to obtain $\rho^*_\text{Ar} = 1/K_{\text{Ar}}$.

Fig. 3 Time constant ration $\tau'/\tau$ for a mixed gas to a single gas system as a function of the electron emission and with the critical current as the parameter, see Equ. (49).

Fig. 4 Plot of the pressure response in the test system, without enhanced outgassing (dashed line) and with outgassing (full line), see Equs. (54) and (55).

Fig. 5 Plot of the ion bombardment induced partial pressure rise in the laboratory test system, as a function of the electron emission for H$_2$, CO and CO$_2$ before glow discharge treatment. The dashed lines fit the experimental points at low emission. They are of slope one, corresponding to a linear relationship in this logarithmic scale.

TABLE CAPTION

Table I Data obtained from a 304 L stainless steel tube before (b) and after (a) an in-situ pure Ar glow discharge cleaning. Partial pressures are given in torr and measured at the middle of the pipe before injecting the argon gas, and some 24 hours after pumpdown, see col. (4) and (8). During critical current measurements, partial pressures are higher mainly due to the impurities injected together with the Ar; CH$_4$, H$_2$O and Ar were found to be decreasing with electron emission. The quantities $\eta_M$, $S_{\text{lin}}$ and $I_c$ were obtained from equ. (41), (42) and (30) respectively. In the last column, $\eta_M$ values are listed that are found from equ. (19) with the $I_c$ measured and $q_{\text{lin}}^M$ as from ref. (10). These are values comparable to the ISR where $s_m = 0$ is assumed.
<table>
<thead>
<tr>
<th>Mass</th>
<th>before measurement</th>
<th>during measurement</th>
<th>after measurement</th>
<th>𝜈_M</th>
<th>S_{lin}</th>
<th>I_c</th>
<th>𝜈_M(s_m=0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 H_2</td>
<td>b 2.3 \cdot 10^{-11}</td>
<td>1.1 \cdot 10^{-8}</td>
<td>1.2 \cdot 10^{-8}</td>
<td>8.8 \cdot 10^{-11}</td>
<td>19</td>
<td>5.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>a 4.7 \cdot 10^{-11}</td>
<td>4.3 \cdot 10^{-9}</td>
<td>5.8 \cdot 10^{-8}</td>
<td>8.8 \cdot 10^{-11}</td>
<td>110</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12 C</td>
<td>b &lt;10^{-9}</td>
<td>2.5 \cdot 10^{-9}</td>
<td>5 \cdot 10^{-8}</td>
<td>8.2 \cdot 10^{-13}</td>
<td>250</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>a &lt;10^{-9}</td>
<td>2 \cdot 10^{-9}</td>
<td>10^{-9}</td>
<td>8.2 \cdot 10^{-13}</td>
<td>3500</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16 CH_4</td>
<td>b 5 \cdot 10^{-13}</td>
<td>4 \cdot 10^{-8}</td>
<td>2.1 \cdot 10^{-7}</td>
<td>1 \cdot 10^{-12}</td>
<td>-0.156</td>
<td>0.18</td>
<td></td>
</tr>
<tr>
<td></td>
<td>a 8 \cdot 10^{-13}</td>
<td>3 \cdot 10^{-8}</td>
<td>6 \cdot 10^{-8}</td>
<td>1 \cdot 10^{-12}</td>
<td>-9.4 \cdot 10^{-2}</td>
<td>0.106</td>
<td></td>
</tr>
<tr>
<td>18 H_2O</td>
<td>b 3 \cdot 10^{-13}</td>
<td>9 \cdot 10^{-8}</td>
<td>5 \cdot 10^{-8}</td>
<td>3 \cdot 10^{-13}</td>
<td>-2.2 \cdot 10^{-3}</td>
<td>2.5 \cdot 10^{-3}</td>
<td></td>
</tr>
<tr>
<td></td>
<td>a 3 \cdot 10^{-13}</td>
<td>6 \cdot 10^{-8}</td>
<td>5 \cdot 10^{-8}</td>
<td>6 \cdot 10^{-13}</td>
<td>-7.7 \cdot 10^{-3}</td>
<td>8.7 \cdot 10^{-3}</td>
<td></td>
</tr>
<tr>
<td>26 C_2H_2</td>
<td>b &lt;6 \cdot 10^{-14}</td>
<td>3 \cdot 10^{-9}</td>
<td>1.5 \cdot 10^{-8}</td>
<td>3 \cdot 10^{-13}</td>
<td>-10^{-14}</td>
<td>490</td>
<td></td>
</tr>
<tr>
<td></td>
<td>a &lt;10^{-9}</td>
<td>&lt;10^{-9}</td>
<td>&lt;10^{-9}</td>
<td>&lt;10^{-9}</td>
<td>&gt;10^5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>28 CO</td>
<td>b 2.1 \cdot 10^{-12}</td>
<td>6 \cdot 10^{-8}</td>
<td>2.6 \cdot 10^{-8}</td>
<td>6.7 \cdot 10^{-8}</td>
<td>5.2 \cdot 10^{-12}</td>
<td>2.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>a 5.2 \cdot 10^{-12}</td>
<td>3 \cdot 10^{-8}</td>
<td>2.2 \cdot 10^{-7}</td>
<td>4 \cdot 10^{-8}</td>
<td>7.1 \cdot 10^{-12}</td>
<td>31.2</td>
<td></td>
</tr>
<tr>
<td>40 Ar</td>
<td>b &lt;6 \cdot 10^{-14}</td>
<td>1.1 \cdot 10^{-4}</td>
<td>1.0 \cdot 10^{-4}</td>
<td>3.6 \cdot 10^{-13}</td>
<td>-7 \cdot 10^{-3}</td>
<td>8 \cdot 10^{-3}</td>
<td></td>
</tr>
<tr>
<td></td>
<td>a 4 \cdot 10^{-13}</td>
<td>9.0 \cdot 10^{-5}</td>
<td>8.0 \cdot 10^{-5}</td>
<td>2.2 \cdot 10^{-11}</td>
<td>-1.6 \cdot 10^{-2}</td>
<td>1.8 \cdot 10^{-2}</td>
<td></td>
</tr>
<tr>
<td>44 CO_2</td>
<td>b 5 \cdot 10^{-13}</td>
<td>5 \cdot 10^{-8}</td>
<td>6 \cdot 10^{-8}</td>
<td>9 \cdot 10^{-9}</td>
<td>5.5 \cdot 10^{-13}</td>
<td>116</td>
<td></td>
</tr>
<tr>
<td></td>
<td>a 4 \cdot 10^{-13}</td>
<td>4 \cdot 10^{-9}</td>
<td>10^{-9}</td>
<td>2 \cdot 10^{-9}</td>
<td>1 \cdot 10^{-12}</td>
<td>1.3 \cdot 10^4</td>
<td></td>
</tr>
</tbody>
</table>

Table I
\[ P(t) \]
\[ P(t)|_{\eta_b = 0} \]

\[ f(t) \]

Time [sec] vs. Pressure \([10^{-6}\text{ torr}]\)