VACUUM SYSTEM DESIGN

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1. INTRODUCTION

In this paper the basic terms used by the vacuum engineer are presented and some useful formulae are also given. The concept of bakeout is introduced and the physics behind it explained. However we will not dwell on the very basics of vacuum system design but concentrate on the effects in electron and proton storage rings which are due to energetic particle bombardment of the vacuum system walls and the ensuing gas desorption which may detrimentally affect the running of the machine. In addition, the problems associated with proton storage rings where the vacuum chamber is at cryogenic temperature are described.

2. BASIC FORMULAE

What interests the electron or proton storage ring vacuum system builder is the molecular density encountered by the circulating particles since it is these residual gas molecules which scatter the circulating particles and, with time, gradually reduce the beam intensity.

Although most vacuum gauges measure the molecular density, conventionally we always refer to pressure, which is a force per unit area. The pressure P is given by:

$$P = \text{const}\ n\ M \langle v^2 \rangle$$

where n is the number of molecules/cm^3

M is the mass of the molecule

and $\langle v^2 \rangle$ is the mean square velocity of the molecule

In the MKS system the unit of pressure is the Pascal (Pa) and

$$1\ \text{Pa} = 1\ N\ \text{m}^{-2}$$

The relation between pressure and molecular density is derived from Avogadro's number and the definition of the gram molecular volume i.e. 22.414 l of gas at 1.013 10^5 Pa (1 atmosphere) and 273 K contain 6.023 10^{23} molecules. Or 1 Pa l of gas contains 2.65 10^{17} molecules at 273 K.

Other units of pressure used very frequently are Torr and millibar where

$$1\ \text{Torr} = 133.33\ \text{Pa}$$

and

$$1\ \text{millibar} = 100\ \text{Pa}$$

At lower temperatures, for a given pressure, the number density of molecules increases since the kinetic energy of the molecule is proportional to the temperature and it is the mean square velocity of the molecule which enters in the expression for the pressure.

Pressures in storage rings are typically below 1 10^{-9} Torr.

3 . CONDUCTANCE

The gas Q (Torr l s^{-1}) flowing to the pump from the vessel being evacuated generally passes through a series of pipes which represent a resistance to flow. This results in a pressure difference P_1-P_2 (Torr) and the conductance C (l s^{-1}) is defined as:

$$C = \frac{Q}{P_1 - P_2}$$

Conductances in series C_1, C_2, C_3, ...add as

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}$$

and conductances in parallel add as

$$C = C_1 + C_2 + C_3$$

Since the conductance is determined by the mean velocity of the gas molecule, and the mean velocity $\bar{v}$ of the molecule for a Maxwellian velocity distribution is given by [1]:

$$\bar{v} = 4\left[\frac{kT}{2\pi M}\right]^{1/2}$$

where k is Boltzmann's constant

and T is the absolute temperature

the conductance varies as:

$$\sqrt{\frac{T}{M}}$$

Conventionally, conductances are given for N_2, $M = 28$.

Useful expressions for the conductance C (l s^{-1}) of a long circular tube and a long elliptical tube in the molecular flow regime (below 10^{-3} Torr) are:

Circular tube, radius R (cm), length L (cm) >> R

$$C = 92.8\left[\frac{R^3}{L}\right]\left\{\left[\frac{T}{300}\right]\left[\frac{28}{M}\right]\right\}^{1/2}$$

Elliptic tube, semi major and minor axes a (cm) and b (cm), length L (cm)

$$C = 130\left[\frac{a^2 b^2}{L}\right]\left[a^2 + b^2\right]^{-1/2}\left\{\left[\frac{T}{300}\right]\left[\frac{28}{M}\right]\right\}^{1/2}$$

The conductance C (l s^{-1}) of an orifice of area A (cm^2) is given by

$$C = 11.6A\sqrt{\frac{T}{M}}$$

4. MONOLAYER

The vacuum engineer is concerned with the efficient removal of adsorbed surface gas. The quantity of surface gas is usually expressed in monolayers. The molecular diameters in Ångström (1 Å=10^{-8} cm) of some gases commonly found in vacuum systems are given in Table 1.

Table 1
The diameters of some molecules

Molecule	Diameter (Å)
Ar	3.2
CO	4.1
He	1.9
H_2	2.4
N_2	3.3
O_2	3.2

Let us calculate how many molecules make a monolayer. If we take N_2, then on 1 cm^2 there are

$$\frac{1}{3.3\ 10^{-8} \times 3.3\ 10^{-8}} = 10^{15} \text{ molecules cm}^{-2}$$

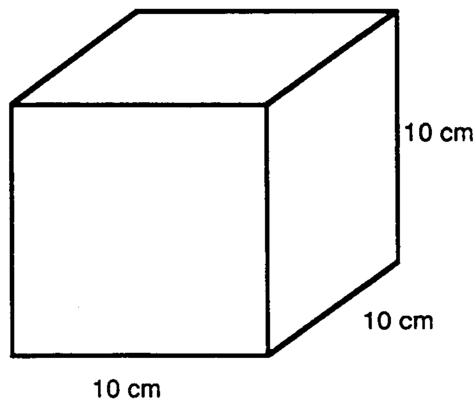


Fig. 1 A box of volume 1 litre with 1 monolayer of gas adsorbed on the surface

What does one monolayer mean to the vacuum engineer? If we take a box of volume 1 litre as shown in Fig. 1 then

$$\text{Volume} = 10^3 \text{ cm}^3 = 1 \text{ litre}$$

$$\text{Surface area} = 6 \text{ x } 10 \text{ x } 10 = 600 \text{ cm}^2$$
$$1 \text{ Monolayer} = 1\ 10^{15} \text{ x } 600 = 6\ 10^{17} \text{ mol. in 1 liter}$$

Since 3.54 10^{19} mol. l^{-1} = 1 Torr at 0°C

$$6\ 10^{17}\ \text{mol. } l^{-1} = \frac{6\ 10^{17}}{3.54\ 10^{19}}$$

$$= \mathbf{1.7\ 10^{-2}\ Torr}$$

Thus a monolayer of gas is a quantity which may cause considerable pressure increases if allowed to desorb into the vacuum system.

5. PUMPING SYSTEMS

To evacuate the system from atmospheric pressure a combination of a rotary pump and a turbomolecular pump can be used. If operated correctly, this combination can provide a clean, oil-free vacuum to pressures below 10^{-8} Torr. These pumps are also used during bakeout to remove the outgassing products from the system.

Dry, oil-free pumps are also available as standard items.

For clean pumping in the ultra-high vacuum range (< 10^{-9} Torr), sputter ion pumps, non evaporable getter (NEG) and Ti sublimation pumps can be used. Together, these pumps can cope with all the gases normally found in clean, all-metal vacuum systems and, by themselves, have lower limit pressures in the 10^{-11} to 10^{-12} Torr range.

For details of the characteristics of each of these pumps the reader is referred to the manufacturers' catalogues.

6. CLEANING METHODS

Before use, all ultra-high vacuum chambers must be chemically cleaned to remove the cutting oils, dust, fingerprints, etc. Since it is the tightly bound surface gas, not removed by the bakeout, which is desorbed by the energetic electrons, ions or photons generated during operation with beam, one criterion for the choice of the chemical cleaning method is that it leaves the vacuum chamber surface with as little desorbable gas as possible. Since this gas is in, or on, the surface oxide layer, the cleaning methods used for Cu and Al involve fluids which chemically remove this sometimes thick, dirty oxide and replace it with a thin, cleaner oxide.

For Cu, two processes are recommended depending on whether the parts are heavily oxidised (A) or machined (B) where the bulk of the oxide has been removed.

A) For heavily oxidised Cu surfaces

1. Vapour degreasing in perchloroethylene (C_2Cl_4) at 121°C.
2. Alkaline soak with ultrasonic agitation for 5 min. in an alkaline detergent at 50°C. The detergent is 1740S (special CERN) supplied by Cleaning Technology, Nyon, Switzerland and is made up to a concentration of 10 g l^{-1}.
3. Tap water rinse.
4. Pickling in HCl (33%) 50% by volume with H_2O 50% at room temperature for 1 to 5 min.
5. Tap water rinse.
6. Acid etch in

H_2SO_4	(96%)	42% by vol.
HNO_3	(60%)	8% by vol.

HCl (33%)	0.2% by vol.	
H_2O to complete		

at room temperature for 30 s to 1 min.

7. Tap water rinse.
8. Passivation in CrO_3 (Chromic acid) 80 g l^{-1}
   H_2SO_4 (96%) 3 cm^3 l^{-1}
   at room temperature for 30 s to 1 min.
9. Running tap water rinse.
10. Cold demineralized water rinse.
11. Dry with filtered air or dry N_2.
10 Wrap in Al foil

B) For machined Cu parts

1. Vapour degreasing in perchloroethylene (C_2Cl_4) at 121°C.
2. Alkaline soak with ultrasonic agitation for 5 min. in an alkaline detergent as in A2) above at 50°C.
3. Tap water rinse.
4. Pickling in HCl (33%) 50% by volume with H_2O 50% at room temperature for 1 to 5 min.
5. Tap water rinse.
6. Passivation in CrO_3 (Chromic acid) 80 g l^{-1}
   H_2SO_4 (96%) 3 cm^3 l^{-1}
   at room temperature for 30 s to 1 min.
7 Running tap water rinse.
8 Cold demineralized water rinse.
9. Dry with filtered air or dry N_2.
10 Wrap in Al foil

For Al two processes are also recommended depending on whether the parts are heavily oxidized or not. The first involves a heavy (µm removed) etch in NaOH and the second a light (about 1500Å removed) etch in alkaline detergent.

A) For heavily oxidised Al surfaces

1. Precleaning by removal of gross contamination, swarf and burrs (steam cleaning excluded).
2. Immersion in alkaline (pH = 9.7) detergent solution at 65°C with ultrasonic agitation for 10 min. The detergent is ALMECO-18 (P3-VR-580-17) manufactured by the Henkel corporation and is made up to a concentration of 20 g l^{-1} with ordinary water.
3. Immediate rinsing inside and out with a cold tap water jet.
4. Rinsing by immersion in a bath of flowing tap water.
5. Alkaline etching by immersion in NaOH at a concentration of 45 g l^{-1} along with 18 g l^{-1} of METEX S449, a wetting agent manufactured by MacDermid, at 45°C for a maximum of 1 to 2 min.
6. Immediate rinsing by immersion in a flowing cold tap water bath.
7. Immersion in a room temperature acid bath containing HNO_3 of concentration 50% by volume (starting from HNO_3 of concentration 65% by weight and specific ravity 1.4) and HF of concentration 3% by volume (starting from HF of concentration 40% by weight and specific gravity 1.13).
8. Immediate rinsing by immersion in a cold flowing demineralized water bath (conductivity < 5 μScm^{-1}).
9. Second rinsing by immersion in a cold flowing demineralized water bath (conductivity < 5 μScm^{-1}).

10. Drying in a hot air oven at about 80°C. Care must be taken to drain all excess water from the tubes before drying as the combination of water and high temperature can form thick oxide layers on the surface.

A) For lightly oxidised Al surfaces

1. Precleaning by removal of gross contamination, swarf and burrs (steam cleaning excluded).
2. Immersion in alkaline (pH = 9.7) detergent solution at 65°C with ultrasonic agitation for 10 min. The detergent is ALMECO-18 (=P3-VR-580-17) manufactured by the Henkel corporation and is made up to a concentration of 20 g l^{-1} with ordinary water.
3. Immediate rinsing inside and out with a cold demineralized water water jet.
4. Rinsing by immersion in a bath of cold flowing demineralized water (conductivity $< 5\ \mu S cm^{-1}$).
5. Drying in a hot air oven at about 80°C. Care must be taken to drain all excess water from the tubes before drying as the combination of water and high temperature can form thick oxide layers on the surface.

The above processes have been found to be effective in cleaning the 128 Cu RF cavity units and the 27 km of Al vacuum chambers in the CERN Large Electron Positron (LEP) storage ring [2,3]. However, it must be remembered that chemical cleaning procedures will never provide atomically clean surfaces since traces of the cleaning solutions will always remain and exposure to air results in adsorption of water vapour, CO_2, etc.

7. THERMAL OUTGASSING

The vacuum pumps have to cope with a molecular flux Q from the surface. The units of Q are molecules s^{-1} or Torr l s^{-1}. The equilibrium pressure P (Torr) obtained when one has a pumping speed S (l s^{-1}) and an outgassing rate Q (Torr l s^{-1}) is given by:

$$P = \frac{Q}{S}$$

Molecules are bound to the surface with a certain binding energy E (eV) and the rate at which the surface coverage N (molecules cm^{-2}) is reduced is given by:

$$\frac{dN}{dt} = -\ \text{const}\ N \exp\left(\frac{-E}{kT}\right)$$

where k is Boltzmann's constant

and T is the absolute temperature

The thermal outgassing rate Q is simply $\frac{dN}{dt}$

Typical values of outgassing rates for clean, baked stainless steel, Cu or Al are around $1\ 10^{-12}$ (Torr l s^{-1} cm^{-2}) and that is mostly H_2.

For unbaked surfaces the outgassing rates are roughly 10 times higher and contain other gases apart from H_2 such as CH_4, H_2O, CO and CO_2 and take longer to pump down to the equilibrium pressure. Figure 2 shows how the outgassing rate depends on the pumping time.

Outgassing rates have to be measured. They cannot be calculated since they depend strongly on the material and the surface treatment i.e. how contaminated the surface is or how well the chemical cleaning has been carried out.

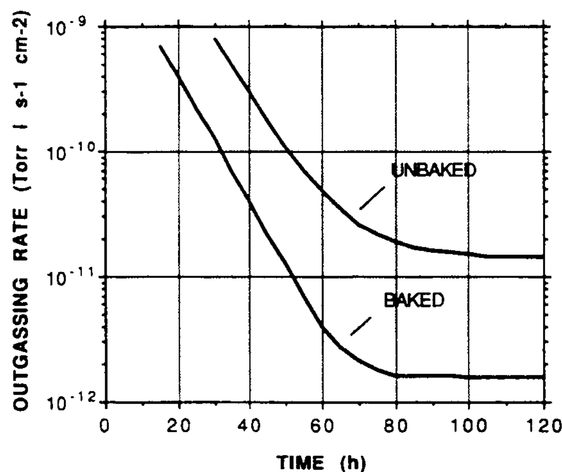


Fig. 2 The time dependence of the outgassing rate

8. BAKEOUT

If, for a given pumping speed, the pressure is not low enough then we must reduce the thermal outgassing rates by reducing the surface coverage N or the temperature T.

$$\frac{dN}{dt} = -\text{const}\, N \exp\left(\frac{-E}{kT}\right)$$

If we increase the temperature for a certain time this will deplete the surface coverage N and when we cool back down to room temperature the outgassing rate will be lower. This is the principle of bakeout. However, if the binding energy E is large, the outgassing rate of molecules from that particular state will be small and will therefore not bother us. It is only those molecules in the low energy binding states and which desorb at ambient temperature which are a nuisance and must be removed. The tightly bound molecules, although they do not desorb i.e. we do not see them, are still present on the surface and, as we shall see later, can be desorbed by energetic ions, electrons or photons.

By integrating the above equation, the time t required to reduce the initial surface concentration of a state of binding energy E by $1/e$ by heating at a temperature T is found to be:

$$\tau = \text{const} \exp\left(\frac{E}{kT}\right)$$

In Table 2 are given some measured binding energies for CO and H_2 on some stainless steels [4,5] and in Table 3 are the values of τ for four binding energies and three bakeout temperatures.

Table 2
Binding energy (eV)

	316 L+N Non-degassed	316 L+N degassed	316 LN	NS 21
α-C O	0.97		1.2	0.9

β-C O	1.72	1.67	1.7	1.55
γ-C O	2.05	1.91	2.2	1.96
δ-C O			2.8	
H_2				0.89

Table 3

τ (s) for different binding energies and bakeout temperatures

E (eV)	200°C	300°C	400°C
0.9	$3.8\ 10^{-4}$	$8.1\ 10^{-6}$	$5.4\ 10^{-7}$
1.7	$1.2\ 10^{5}$	$8.6\ 10^{1}$	$5.2\ 10^{-1}$
2.0	$1.9\ 10^{8}$	$3.7\ 10^{4}$	$9.1\ 10^{1}$
2.8	$6.4\ 10^{16}$	$4.0\ 10^{11}$	$8.8\ 10^{7}$

1 hour = $3.6\ 10^3$ s, 1 day = $8.6\ 10^4$ s, 1 week = $6.0\ 10^5$ s, 1 year = $3.0\ 10^7$ s

9. SYNCHROTRON RADIATION INDUCED GAS DESORPTION

When relativistic electrons or positrons are in circular motion they radiate energy in the form of synchrotron radiation. This electromagnetic radiation has a spectrum extending from the infrared to, in some cases, many keV. These energetic photons hit the wall of the vacuum chamber, produce photoelectrons and desorb gas which is tightly bound to the surface. The quantity of interest is the photon induced gas desorption yield defined as the number of desorbed gas molecules per incident photon.

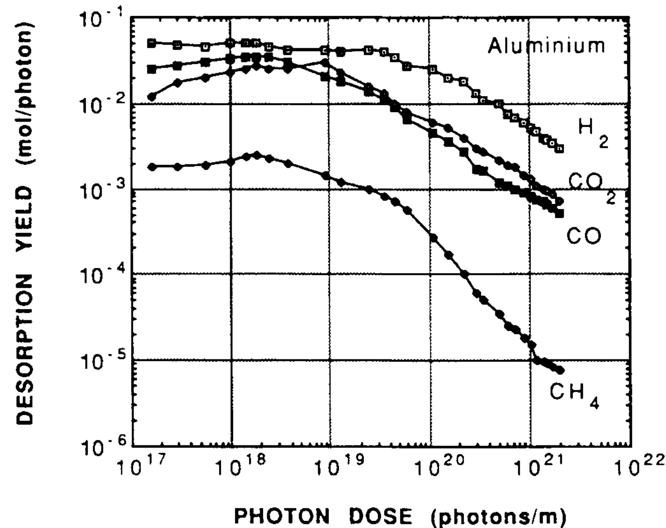


Fig. 3 The photon induced gas desorption yield for baked Al at 2.95 keV critical energy as a function of the total photon dose

The photon induced neutral gas desorption yields for a baked Al alloy vacuum chamber as a function of the photon dose are shown in Fig. 3. There it can be seen that the gases desorbed are firstly H_2 followed closely by CO and CO_2, all in the 1 10^{-2} molecules/photon range, with CH_4 about a factor of 10 lower. With increasing photon dose all desorption yields decrease but the CH_4 decreases much faster than the other gases. After a dose of 2 10^{21} photons/m the H_2 has decreased by a factor of 13, CO and CO_2 by a factor of 10 and CH_4 by a factor of 300.

In Fig. 4 the corresponding results for Cu are shown. It can be seen immediately that, compared to Al, the initial desorption yields are all about a factor of 10 lower. However the rate of decrease with photon dose is also lower, in that after a dose of 2 10^{21} photons/m the desorption yields have only decreased by a factor of 10. Again it is H_2 which has the largest desorption yield followed closely by CO and CO_2 with CH_4 lower still.

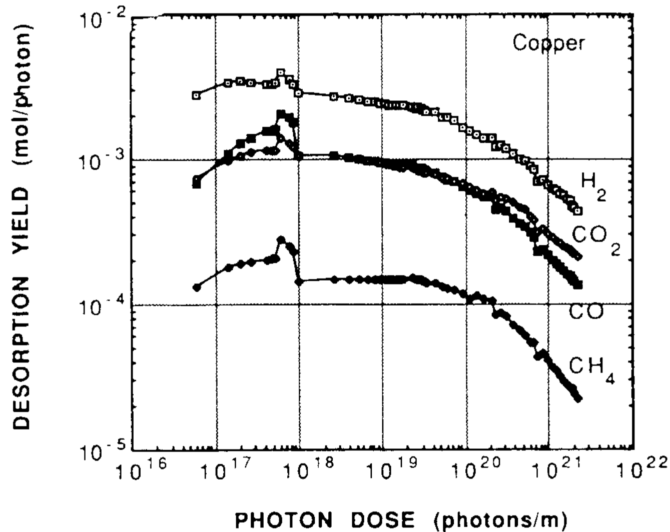


Fig. 4 The photon induced gas desorption yield for baked Cu at 2.95 keV critical energy as a function of the total photon dose

With the advent of non-evaporable getters (NEG) the total quantity of gas desorbed by the synchrotron radiation is important in deciding how much NEG to install and in predicting how often it must be reconditioned during the operation of the machine. By integration of the desorption yields with respect to photon dose, the total number of molecules desorbed per metre of chamber as a function of photon dose may be obtained. A more practical number is the amount of gas desorbed in Torr litres per metre of chamber, where 1 Torr litre = 3.3 10^{19} molecules at 20°C. This integration has been carried out for Al and the results are shown in Fig. 5.

For the Al, which had the highest desorption coefficients, it can be seen that, after 3 10^{21} photons/m, almost 1 Torr l/m of H_2 had been desorbed, 0.1 Torr l/m of CO and CO_2 but only 4 10^{-3} Torr l/m of CH_4.

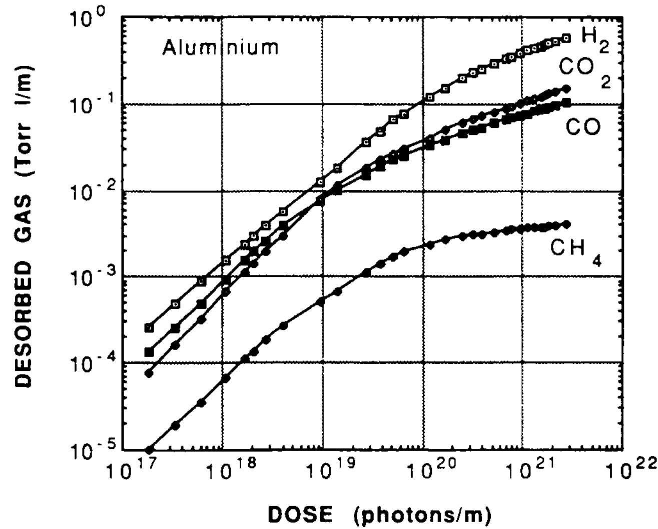


Fig. 5 The quantity of gas desorbed from Al as a function of the total photon dose

Another practical piece of information useful in the design of pumps for vacuum systems exposed to synchrotron radiation is how much gas has to be removed before the desorption coefficients drop below a certain value. These results are shown in Fig. 6 for Al.

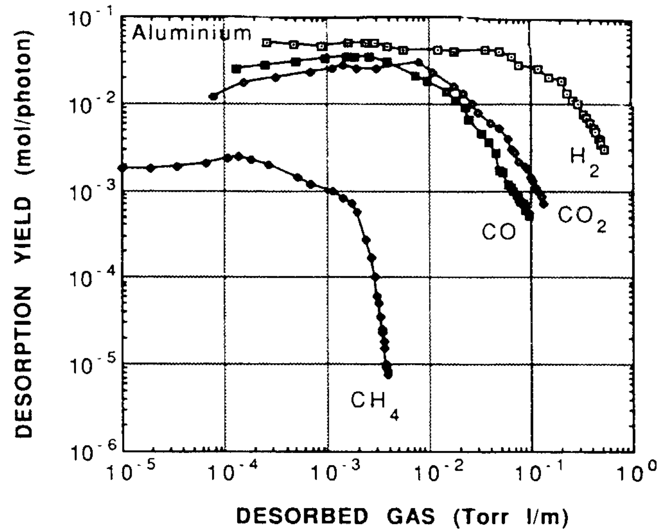
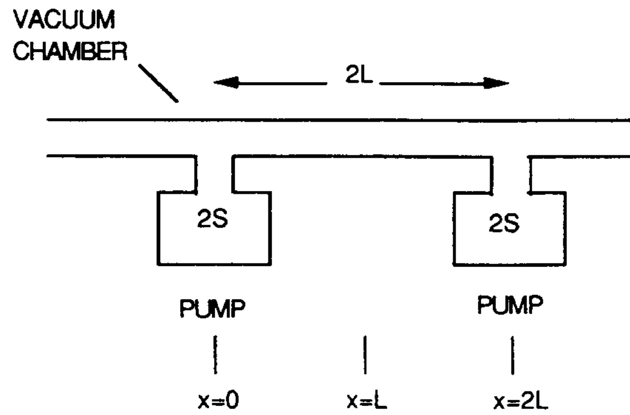


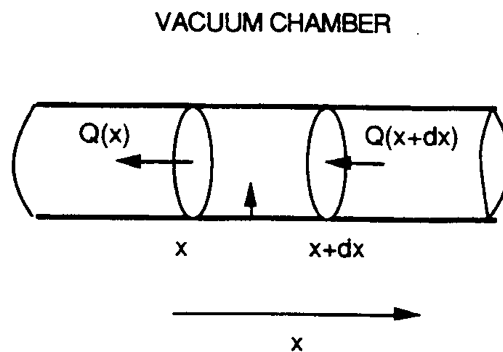
Fig. 6 The photon-induced gas desorption yields as a function of the quantity of desorbed gas

10. SIMPLE MACHINE

An outline of a simple machine is given below. It essentially consists of a long vacuum chamber pumped at regular intervals and this type of structure is repeated around the machine. Each pump has a pumping speed of $2S$ and there is a distance of $2L$ between pumps.



If we consider a section of the vacuum chamber as shown below,



then the gas flow Q through the chamber is given by:

$$Q = -c\frac{dP}{dx}$$

where P is the gas pressure (Torr)
V is the volume per unit length of tube (l m^{-1})
w is the perimeter of the tube (m)
c is the specific conductance of the tube (l s^{-1} m)
a is the gas desorption per unit length of tube (Torr l s^{-1} m^{-1})
q is the gas desorption per unit area of tube (Torr l s^{-1} m^{-2})
$a = q\,w$

The change in number density of molecules in the volume element Vdx between x and $x + dx$ is

$$V\ dx\frac{dP}{dt} = a\ \ dx + c\left[\frac{dP}{dx}\right]_{x+dx} - c\left[\frac{dP}{dx}\right]_{x}$$

$$V\frac{dP}{dt} = a + c\left[\frac{d^2P}{dx^2}\right]$$

In the steady state $$\frac{dP}{dt} = 0$$

thus the equation to be solved is: $$\frac{d^2P}{dx^2} = -\frac{a}{c}$$

Boundary conditions

By symmetry at $x = L$ $$\frac{dP}{dx} = 0$$

At $x = 0$ and $x = 2L$ $$P = \frac{aL}{S}$$

and $$c\frac{dP}{dx} = aL$$

The final solution is $$P = \frac{aL}{S} + \frac{aLx}{c} - \frac{ax^2}{2c}$$

The maximum pressure $$P_{max} = \frac{aL}{S} + \frac{aL^2}{2c}$$

The average pressure $$P_{av} = aL\left[\frac{1}{S} + \frac{L}{3c}\right]$$

11. PROTON STORAGE RINGS

In proton storage rings the energetic protons can ionize the molecules of the residual gas. These positive ions are then repelled by the positive space charge of the protons and can bombard the vacuum chamber walls with energies up to a few hundred eV depending on the proton beam current. The energetic ions desorb tightly bound surface gas which increases the pressure and hence, in turn, the ion bombardment. Thus we have a positive feedback process which may result in a pressure runaway.

The beam induced gas desorption is pressure dependent, thus we must introduce a pressure dependent term in addition to the thermal outgassing term in the differential equation describing the behaviour of the pressure. This term (Torr l s^{-1} m^{-1}) can be written as:

$$10^3 P\eta\sigma\frac{I}{e}$$

where σ is the ionisation cross-section of the molecule for high energy protons ($0.25\ 10^{-22}$ m^2 for H_2)
I is the proton beam current (A)
P is the pressure (Torr)
e is the electronic charge ($1.6\ 10^{-19}$ C)
and 10^3 comes from the units used.

The differential equation then becomes

$$V\frac{dP}{dt} = a + bP + c\left[\frac{d^2P}{dx^2}\right]$$

where

$$b = 10^3\,\eta\sigma\frac{I}{e}$$

For steady state conditions $\frac{dP}{dt} = 0$ and the equation to be solved is:

$$\frac{d^2P}{dx^2} = -\omega^2 P - \frac{a}{c}$$

where

$$\omega^2 = \frac{b}{c}$$

The solution has the form

$$P = \frac{a}{c\omega^2}\left[\frac{\cos\omega(L-x)}{\cos\omega L - \frac{\omega c}{S}\sin\omega L} - 1\right]$$

A solution only exists if

$$\cos\omega L - \frac{\omega c}{S}\sin\omega L > 0$$

or

$$\omega\tan\omega L < \frac{S}{c}$$

In practice this reduces to the stability criterion

$$\eta\, I < \text{constant (depending on } S, C \text{ and } L)$$

As an example in the CERN proton storage rings (ISR) the parameters of the vacuum system were such that the product ηI had to be less than 25.7. Since proton beam currents could reach 50 A this meant that the desorption yield η had to be less than 0.5 molecules/ion for stability.

12. COLD PROTON STORAGE RINGS

In the CERN Large Hadron Collider (LHC) and the American Superconducting Super Collider (SSC) projects, protons of 7.7 TeV and 20 TeV respectively will circulate in a vacuum chamber at cryogenic temperatures. The relativistic protons will emit a significant amount of synchrotron radiation thus there will be all the photon induced gas desorption as well as the pressure stability problems described in the previous sections. In addition, although the vacuum chamber at cryogenic temperatures is a cryopump with a very large pumping speed for the desorbed gases, the combination of the photon induced gas desorption and the pumping surface may turn out to be somewhat of a liability.

In the LHC the superconducting magnets will operate in a bath of superfluid He at 1.9 K. The power coming from beam induced losses in the vacuum chamber walls and from synchrotron radiation will be absorbed at 5 to 10 K by a separate inner screen. The synchrotron radiation desorbs H_2, CH_4, CO and CO_2. from the surface and near surface of the screen and these gases are immediately cryopumped by the surrounding surfaces. Thus, with continued photon bombardment, the coverage of these gases will gradually build up on the surface and, since the desorption yields defined above increase with surface coverage, the

pressure may become unstable. For example, the desorption yield for 5 keV H_2^+ desorbing H_2 from a layer three monolayers thick is 5 10^4 mol/ion.

The gas which is physisorbed on the cold screen surface has a thermodynamic vapour pressure. For temperatures <10 K only the vapour pressure of H_2 will be significant. Initially, when the surface coverage is less than a monolayer, the pressure will be very low and completely insignificant. But, as the first monolayer becomes completed, the vapour pressure rises dramatically and exceeds 10^{-6} Torr at 5 K as shown in Fig. 7. Such a high pressure is unacceptable in a storage ring such as the LHC since the beam-gas lifetime is less than 20 minutes instead of the required 24 hours.

It is important, therefore, that the screen surface be as clean as possible initially so that the photon induced gas desorption is small and the time to build up a thick layer is long.

Since it is not pure H_2 which is cryopumped but a mixture containing H_2, CH_4, CO and CO_2, it is uncertain what the vapour pressure of this composite layer will be. If the vapour pressure of the H_2 component is suppressed then this will be an advantage but the pressure instability due to the ion bombardment will not be affected.

An additional complication is that the choice of the screen surface is imposed. For reasons of beam stability, the screen wall must have a high electrical conductivity and a suitable material is pure Cu. However these chambers are in the 9.5 Tesla magnetic field of the superconducting dipole bending magnets which, from time to time, may quench. When this occurs, the magnetic field drops from 9.5 Tesla to zero in about 0.3 s and hence induces large currents in the screen which, in turn, produce large forces.

A pure Cu screen, with its low electrical resistance would have large induced currents and large forces which would deform it. The screen will therefore be made of stainless steel for mechanical strength with a 0.1 mm layer of Cu electrodeposited on the interior for the beam stability (Fig. 8). Thus it is this electrodeposited Cu layer which is bombarded by photons and which should be as free of desorbable gas as possible.

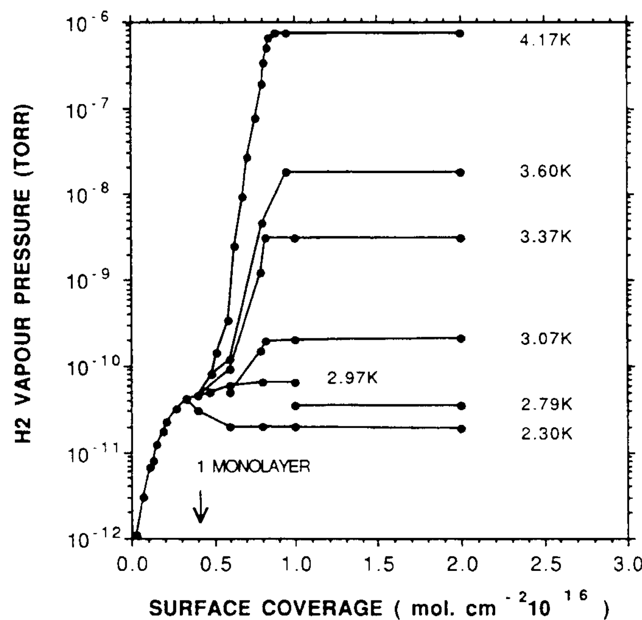


Fig. 7 The vapour pressure of H_2 as a function of surface coverage for different temperatures

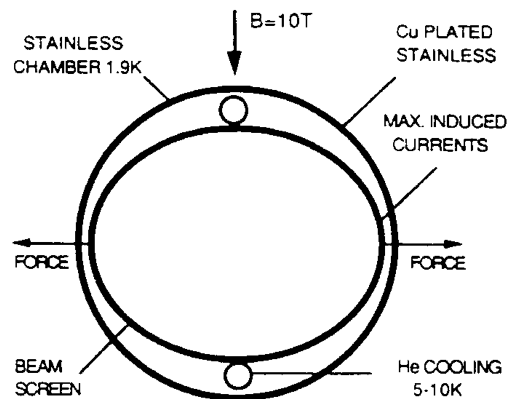


Fig. 8 A cross section of the LHC vacuum chamber with its Cu-plated stainless steel screen

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