Vacuum Technology for Superconducting Colliders

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Abstract

In high energy proton-proton colliders such as the CERN Large Hadron Collider (LHC) project with a centre of mass collision energy of over 14 TeV and the American Superconducting Super Collider (SSC) where the centre of mass collision energy reaches 40 TeV the relativistic protons lose energy in the form of synchrotron radiation. For adequate beam-residual gas lifetimes in these machines the pressure should typically be in the 10^{-10} Torr range. However the synchrotron radiation impinging on the walls of the vacuum chamber desorbs gas and may result in large pressure increases detrimental to the operation of the collider. To achieve the required strong bending in these machines it is necessary, in the case of the LHC, to employ dipole fields up to 9.0 T which need superconducting magnets operating at 1.9 K. The vacuum chamber is therefore at cryogenic temperature and functions as a cryopump. At first sight this free cryopumping may appear beneficial but in practice introduces several liabilities-for example, only a few monolayers of cryopumped H_2 already has a vapour pressure at 5 K in excess of 10^{-6} Torr. These and other effects and constraints on the design of the cold vacuum system will be described in detail.

I. INTRODUCTION

In high energy accelerators such as the CERN Large Hadron Collider (LHC) and the American Superconducting Super Collider (SSC) protons will be accelerated and stored at energies up to 7.2 TeV and 20 TeV respectively in a vacuum chamber at cryogenic temperatures. The relativistic protons, when accelerated in the magnetic fields of the bending magnets, will emit synchrotron radiation with a critical energy of 51.2 eV in the LHC and 284 eV in the SSC. The synchrotron radiation photons impinge on the walls of the vacuum chamber and desorb tightly bound gas which can give gas loads several orders of magnitude above the normal thermal outgassing. Although the vacuum chamber at cryogenic temperatures is a very efficient 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.

It is these effects associated with gas desorption by synchrotron radiation from cold surfaces and other effects which place severe constraints on the vacuum engineer concerned with the design and understanding of these vacuum systems that will be described in this paper.

II. PRESSURE REQUIREMENTS

What interests the 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. In order that the beam lifetime is not unduly reduced by this process low pressures are required.

Since the vacuum chambers in these machines are at cryogenic temperatures the meaning of pressure has to be clearly defined.

Although most vacuum gauges measure the molecular density, conventionally we always refer to pressure, which is a force per unit area. For a given gas density the pressure is proportional to the temperature. For example at 293 K 1 Torr contains 3.3 10^{16} mol cm^{-3} and at 5 K 1 Torr contains 1.93 10^{18} mol cm^{-3}. Thus, when converting a gauge reading to molecular density the gas temperature must be known.

In the case of the LHC, CO pressures in the low 10^{-10} Torr range at 5 K are required for beam-gas lifetimes in excess of 24 hours.

III. SYNCHROTRON RADIATION

The characteristics of the synchrotron radiation in the two machines, such as the critical energy, power density and the number of photons per second incident on the vacuum chamber wall along with the machine parameters which determine them are given in Table 1.

Table 1
LHC and SSC Parameters

	LHC	SSC
Bending radius (m)	2700.27	10100
Energy (TeV)	7.3	20.0
Beam current (mA)	851.0	71.7
Critical energy (eV)	51.2	284.0
Photon flux (s^{-1} m^{-1})	1.6 10^{17}	1.0 10^{16}
Synchrotron Radiation Power loss (W m^{-1})	0.41	0.14

In both the LHC and the SSC the required dipole magnetic fields of 9.0 T and 6.76 T respectively are provided by superconducting magnets. In the case of the SSC the magnets run at 4.35 K but to obtain the 9.0 T in the LHC the magnets must operate at 1.9 K and hence the vacuum chamber is also at that temperature.

To absorb the synchrotron radiation power at 1.9 K would require an excessive amount of refrigeration thus a separate inner screen, a so-called beam screen, is necessary to absorb the power at a higher temperature.

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The more than a factor of 10 higher beam current in the LHC means that many effects such as the power loss and the coupling impedances are more important. It is for this reason that we have concentrated on a collider with the LHC parameters.

IV. BEAM SCREEN

To minimize the coupling impedance of the beam screen the interior surface must have a high electrical conductivity and suitable materials would be Al or Cu. However, it must be remembered that the beam screen is in a large dipole magnetic field which decreases the conductivity because of the magnetoresistive effect. An additional effect arises in the case of magnet quenches where the rapidly changing decreasing magnetic field induces large currents and hence large forces in the beam screen. This is shown schematically in Figure 1 for the LHC where the proposed rectangular cross-section optimises the horizontal and vertical apertures available for the beam.

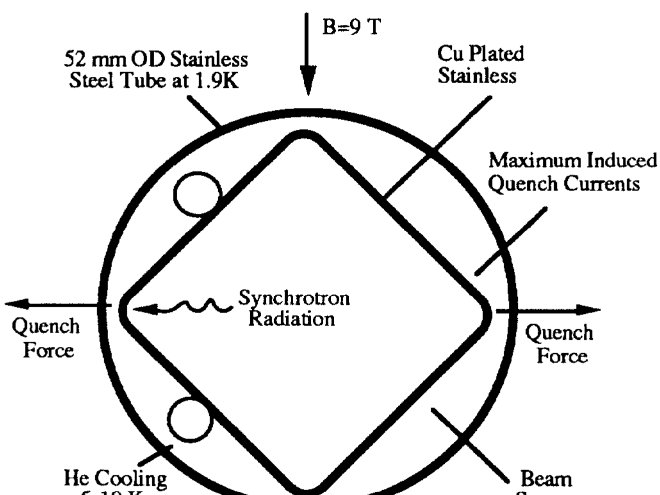

Figure 1. A schematic cross-section of the beam screen in the 1.9 K vacuum chamber.

For example in the LHC it is estimated that, during a quench, the magnetic field would decrease at about 30 T s^{-1} and would induce forces of 15 tons m^{-1} in a 1 mm thick Cu beam screen causing permanent deformation. The magnitude of these quench induced forces excludes the use of thick layers of such high conductivity metals as Al and Cu. The beam screen, therefore, will consist of an inner layer of Cu of sufficient thickness compatible with impedance requirements but sufficiently thin to minimise quench induced forces deposited on an outer tube of a low magnetic permeability material such as stainless steel to provide the necessary mechanical strength.

Since the conductivity of the Cu decreases with increasing temperature, a practical upper limit based on impedance considerations is 30 K.

V. SYNCHROTRON RADIATION INDUCED GAS DESORPTION

Synchrotron radiation photons impinging on the side wall of the vacuum chamber can desorb large quantities of gas. The desorption mechanism is complicated in that it is a two stage process whereby the primary photons produce photoelectrons which subsequently desorb gas by electron stimulated desorption [1], [2]. Also the primary photons are scattered and reflected thus producing desorption from all over the vacuum chamber surface although the primary photons hit along only one side of the chamber [3].

The photon induced neutral gas desorption yields at 63.5 eV critical energy, close to that of the LHC, for an unbaked Cu plated stainless steel chamber at room temperature as a function of the photon dose [4] are shown in Fig. 2. There it can be seen that the gases desorbed initially, in order of importance, are H_2, CO_2, CO, H_2O and CH_4.

All gases during the long exposure to photons exhibited the same behaviour, increasing their yields with dose until they reached a maximum and then decreasing with dose. Although H_2O showed the largest increase with dose before decreasing, the final yield measured after a dose of 1.25 10^{21} photons/m was still above the initial by a factor of about 2.7.

After the maximum photon dose all desorption yields were decreasing and showing no signs of levelling off.

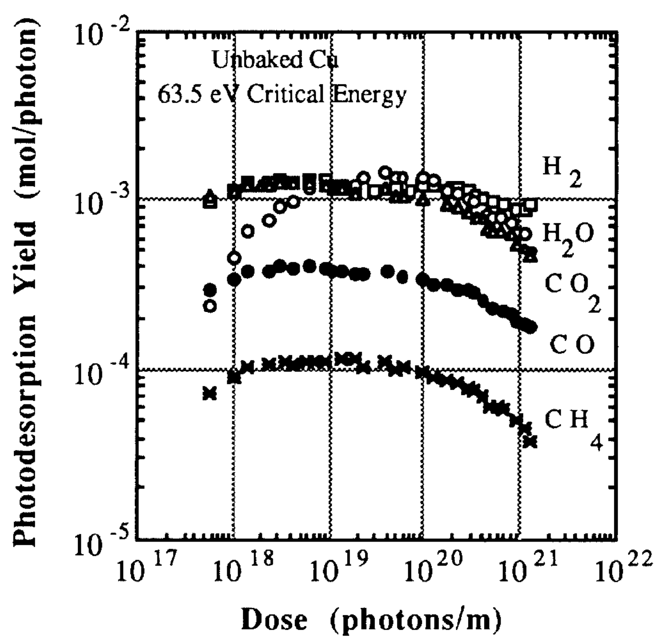

Figure 2. The photon induced gas desorption yields from an unbaked, 100 mm diameter, Cu plated stainless steel chamber as a function of photon dose at 63.5 eV critical energy.

In the critical energy range of ε between 12 eV and 284 eV the initial desorption yields scale as ε^a [4] where a lies between 1.08 and 1.33 depending on the gas species.

By integration of Figure 2 the total quantity of each gas desorbed was obtained and this is shown in Figure 3. The equivalent of about 0.5 monolayers of H_2, H_2O and CO_2 were desorbed after a photon dose of 1.25 10^{21} photons/m followed by 0.1 monolayers of CO and 3 10^{-2} monolayers of CH_4.

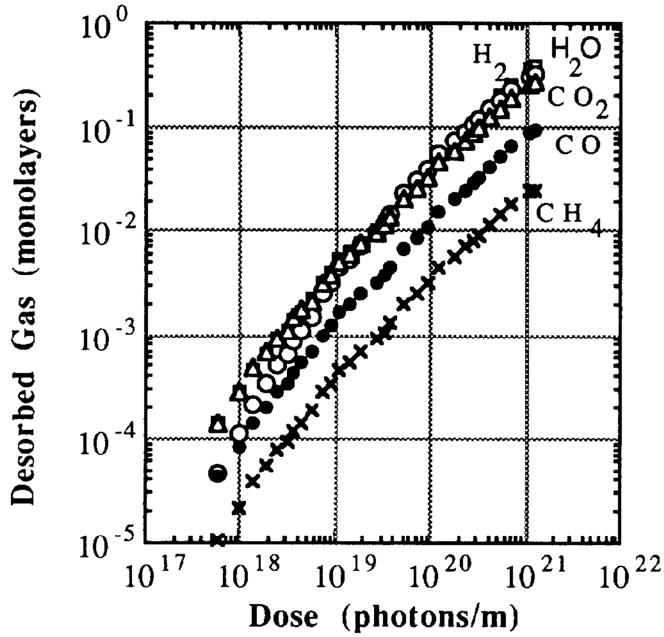

Figure 3. The total quantity of desorbed gas as a function of the photon dose.

Since the beam screen will operate at around 10 K, these desorbed gases will be pumped (physisorbed) by its large condensing surface and slowly build up thick layers.

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 [5] and exceeds 10^{-6} Torr at 5 K as shown in Figure 4. Such a high pressure is unacceptable in a storage ring such as the LHC or the SSC since the beam-gas lifetime would be several 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, H_2O, 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 another effect which is the pressure instability due to the ion bombardment will not be affected.

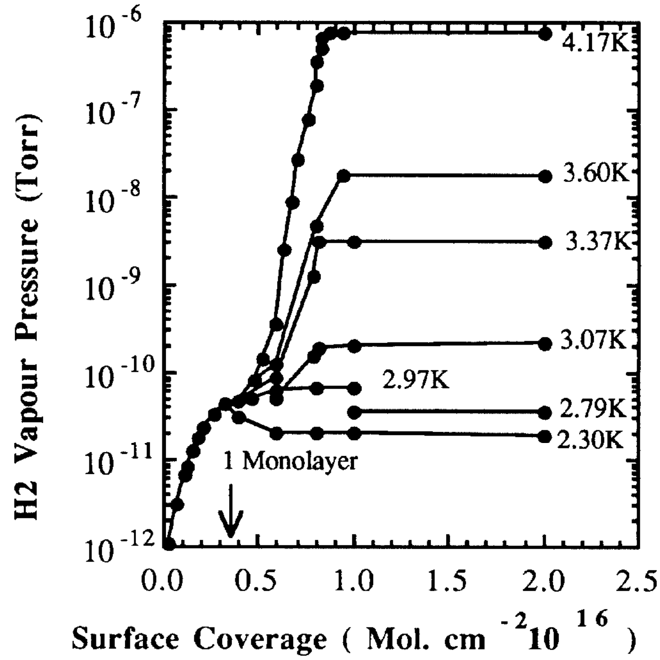

Figure 4. The vapour pressure of H_2 as a function of surface coverage for different temperatures.

VI. ION INDUCED PRESSURE INSTABILITY

The circulating proton beam will ionize the molecules of the residual gas which will then be accelerated towards the screen wall by the repetitive effect of the positive potential of the bunches of protons (~ 300 eV for 851 mA in the LHC). These relatively energetic ions will then desorb all species of gas from the accumulated layer. The resulting increase in pressure leads to an increase in the ion bombardment and hence the gas desorption. This gives another dynamic pressure component: the notorious "pressure bump" mechanism of the CERN Intersecting Storage Rings (ISR) which led to unstable runaway pressures for beam currents in excess of a certain critical value.

Here, as in the case of synchrotron radiation above, there will be a progressively increasing effect as the desorption coefficients increase with beam dose and the accumulated surface gas coverage. At a certain threshold value of the product of beam current and desorption coefficient an avalanche will occur resulting in a pressure run-away and loss of the beam [6].

Fortunately, the high linear pumping speed of the cold surfaces in the LHC and in the SSC vacuum systems helps to raise the threshold and, for H_2, stability will be assured in the LHC if the product of the ion induced gas desorption yield η and the beam current I does not exceed 1300 A. The corresponding figure for CO is 700.

Since the η for 300 eV ions bombarding a 'clean' metal surface is typically ~ 5 mol. ion^{-1}, it is clear that, initially, the product η I is well below the stability limit.

However as the coverage of gas increases on the pumping surface, so does the desorption yield and for thicknesses of many monolayers it can have values as high as 10^4 mol ion^{-1}

[7] as shown in Figure 5. Thus it is important that this build-up of gas on the screen surface be as slow as possible i.e. the synchrotron radiation induced gas desorption be a minimum. This implies that the inner screen surface should initially be as free of desorbable gas as possible.

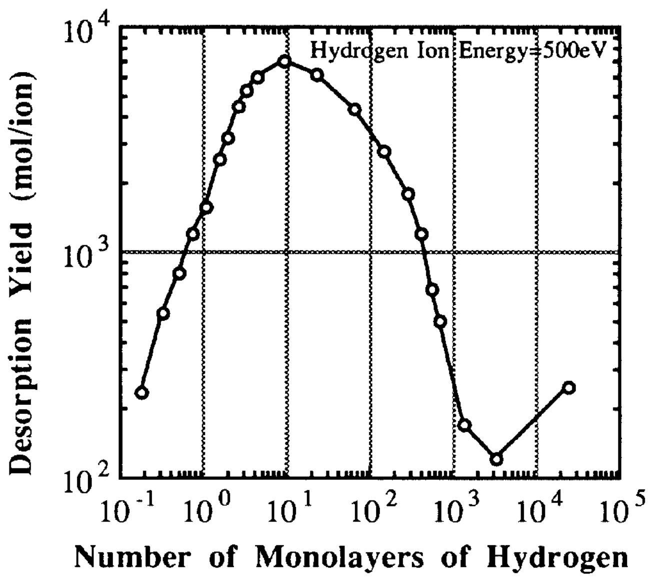

Figure 5. The desorption yield for 500 eV H_2 ions incident on thick condensed H_2 layers.

An obvious way of reducing the amount of adsorbed gas is by heating. However, any heat treatment must not increase the electrical resistivity of the Cu layer above certain limits. Thus once more the vacuum engineer faces constraints in his options.

VII. ELECTRON MULTIPACTORING

With bunched proton beams, pressure rises can occur due to electron multipactoring driven by the electric field of the passing proton bunches [8]. An electron is accelerated towards the bunch, traverses the vacuum chamber and produces secondary electrons from the opposite wall which in turn are accelerated towards the next bunch. If the secondary electron yield is greater than unity, and if the time between bunches is correct, a resonance condition is fulfilled -multipactoring- and large electron currents bombard the chamber walls. These electrons can desorb gas from the surface causing large pressure increases.

A simple calculation with the LHC parameters reveals that the threshold currents for multipactoring are in the range of the LHC beam currents.

VIII. PERFORATED BEAM SCREEN

The major problems, limitations and unpredictable behaviour of the LHC vacuum system all stem from the build-up of the condensed gas layer. The much praised super cryo-pump becomes, even if not a nightmare, a long term liability. A modification of the screen temperature will not change the situation. Operating the screen at 1.9 K for example would only reduce the thermodynamic vapour pressure of H_2 while temperatures higher than 30 K are excluded for beam stability reasons. All other effects seem unaffected by temperature changes within this range.

The introduction of distributed pumping holes in the screen will, however, dramatically modify the LHC vacuum behaviour [9]. Suppose that 1% of the screen surface is considered to be perforated with holes which communicate to the magnet vacuum tube at 1.9 K - holes which are assumed to be perfectly gas transparent and perfectly opaque to synchrotron radiation. If the total pumping speed of the inner beam screen surface is S ls^{-1} then for 1% holes their pumping speed s=S/100 ls^{-1} (Figure 6).

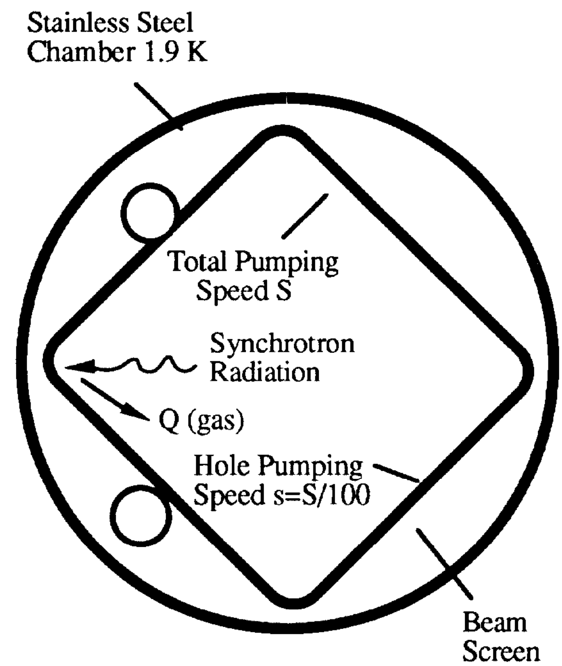

Figure 6. A schematic of the beam screen showing the desorbed gas and the wall and hole pumping speeds.

When the machine is first put into operation the initial pressure will be Q/S Torr where Q is the quantity of each gas desorbed by the synchrotron radiation (Torr ls^{-1}) and S is the pumping speed of the surface for each particular gas. The amount of gas pumped by the holes is P.s (Torr ls^{-1}) i.e. it increases as the pressure increases.

If we consider only H_2, then as the H_2 slowly builds up on the beam screen surface the thermodynamic vapour pressure of H_2 will slowly increase and, if there were no holes, it would increase to its value corresponding to the temperature of the screen e.g. 10^{-6} Torr at 4.2 K. The holes, however, will pump a fraction of this H_2 and an equilibrium will be reached when the quantity of desorbed gas equals the quantity swallowed by the holes i.e. Q=P.s. With the holes the equilibrium pressure of H_2 is therefore given by Q/s which is, for 1% holes, a factor of 100 above the initial H_2 pressure and the extra gas load condenses continually on the 1.9 K surface where its vapour pressure is negligible.

For the other gases their pressures remain unchanged at Q/S since their vapour presures at the temperature of the beam screen are not dependent of the layer thickness.

The temperature and temperature uniformity of the screen become unimportant. They only affect the equilibrium coverage on the screen and, of course, the time to achieve this. However the temperature should be kept constant and, in particular, not be allowed to rise during machine operation. The condensing cryo-surface of the magnets may operate at any temperature which keeps the thermodynamic vapour pressure of H_2 low enough, e.g. 3 K for 10^{-10} Torr after the build-up of several or more monolayers.

However, should the photon induced gas desorption be such that the pressure increase of 100 is too high and decreases the beam-gas lifetime, there will be a need for periodic warming up and cleaning of the screen. However, the screen should at all times be kept warmer than the magnet bore to prevent contamination by retro-diffusion, especially when the machine is not operating.

IX. BEAM-PERFORATION INTERACTIONS

The vacuum engineer is not free to choose either the number or the diameter of the perforations in the beam screen since he must bear in mind that the holes represent discontinuities for the image currents of the beam and result in a beam coupling impedance.

An additional effect comes in the high frequency range from the real part of the impedance. Power is coupled through the holes into the coaxial space between the beam screen and the vacuum chamber and propagates in synchronism with the beam, gradually building up in strength and leaking back into the beam screen further adding to the real part of the coupling impedance [10].

This power is dissipated in both the outer beam screen wall and the 1.9 K inner vacuum chamber wall. For example, in the LHC, with both walls in stainless steel i.e. the same resistivity, for 5% of the surface covered with 2.5 mm diameter holes and 1 mm beam screen wall thickness the power dissipated per metre in the 1.9 K surface is 0.12 W/m whereas the calculated heat leak into the 1.9 K is 0.1 W/m. Thus 5% of 2.5 mm diameter holes more than doubles the heat load on the cryogenic system. For 5% of 1 mm diameter holes the power dissipation in the 1.9K surface is negligible.

The beam screen must be supported in the 1.9 K tube, and the presence of dielectric and preferably lossy support structures in the coaxial space could reduce considerably the power dissipated at 1.9 K. The supports would, of course, be tied thermally to the beam screen.

The supports must be designed with care since it must be remembered that if there are any conducting loops there may be sufficiently large induced voltages during a quench and hence the risk of spot welding the support structure to the 1.9 K tube.

Possibly more critical is the low frequency imaginary (inductive) part of the impedance coming from the holes. An advantage may be gained by having short slots rather than round holes. For example, a slot 10 mm x 1 mm has an inductive impedance about a factor of 2 less than 10 holes each of 1 mm diameter [11].

X. CONCLUSIONS

It has been shown that, when designing vacuum systems in which synchrotron radiation is incident on surfaces at cryogenic temperatures, the vacuum engineer may not be completely free to choose the parameters.

Because of the power radiated by the synchrotron radiation, a screen at a higher temperature than the vacuum chamber may be necessary to intercept this radiation.

Beam stability criteria impose strict upper limits on the electrical resistivity of the beam screen inner wall, and hence the temperature, and also the diameter of the pumping holes in the beam screen.

It is imperative that the vacuum engineer must ensure that the surfaces hit by the synchrotron radiation are as clean as possible so that the pressure increases, which are determined by the diameter and number of the pumping holes, are consistent with the required beam-gas lifetimes and the time to build up thick layers of condensed gas is long i.e. months not days.

XI. ACKNOWLEDGEMENTS

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