The Cold Vacuum System of the Large Hadron Collider

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Abstract

In the CERN Large Hadron Collider (LHC) two 7 TeV proton beams will circulate in a storage ring 27 km in circumference in cold bore vacuum chambers at 1.9 K. The relativistic protons emit synchrotron radiation which deteriorates the vacuum situation by desorbing gas. An inner beam screen at some intermediate temperature (probably 5-20K) will be necessary to protect thermally the cold bore. Nuclear scattering on the residual gas results in decreased beam lifetimes and the deposition of the high energy protons in the superconding magnets which may then quench. The cold beam screen can only function to a limited extent as a cryopump. For example, only a few monolayers of condensed H_2 already have a vapour pressure at 4.2 K of 7 10^{-7} Torr; in addition, beam induced ion and electron bombardment of the condensed layer can cause vacuum instabilities. Perforations in the beam screen can limit the pressure increases by providing steady cryopumping on the 1.9 K cold bore.

1. INTRODUCTION

The LHC vacuum system will consist of two rings about 27 km in circumference in which two 530 mA beams of protons at an energy of 7.0 TeV will circulate [1]. Of the 54 km total length, almost 48 km will be at 1.9 K, the temperature of the superconducting magnets. Due to the centripetal acceleration in these bending magnets each beam will emit a synchrotron radiation flux of 9.6 10^{16} photons s^{-1} m^{-1} with a critical energy of 45.4 eV and a power of 0.22 W m^{-1}.

To absorb this power from both beams at 1.9 K would require an excessive amount of refrigeration and separate inner beam screens at a higher temperature will be necessary. These screens will also carry the beam image currents which will dissipate a further 0.15 W m^{-1} per beam.

The radiation, which impinges on the inner surface of the beam screen, will desorb tightly bound gas and give rise to a gas load which will exceed that due to thermal outgassing by many orders of magnitude. Due to the low temperature, the screen will re-pump much of this gas. This, combined with the photon induced desorption of this now weakly bound gas, turns out to give rise to a number of problems not encountered in warm vacuum systems.

A beam lifetime from residual gas nuclear scattering in excess of 100 hours is required. This implies a H_2 gas density $\leq 9.2\ 10^{8}$ mol cm^{-3} (i.e. $\leq 9.5\ 10^{-10}$ Torr at 10 K), or correspondingly less for heavier gases (e.g. $\leq 7.5\ 10^{7}$ mol cm^{-3} for CO_2).

2. BEAM SCREEN

The construction of the beam screen is fully described in another paper published at this conference [2], but for completeness it is shown schematically in Figure 1.

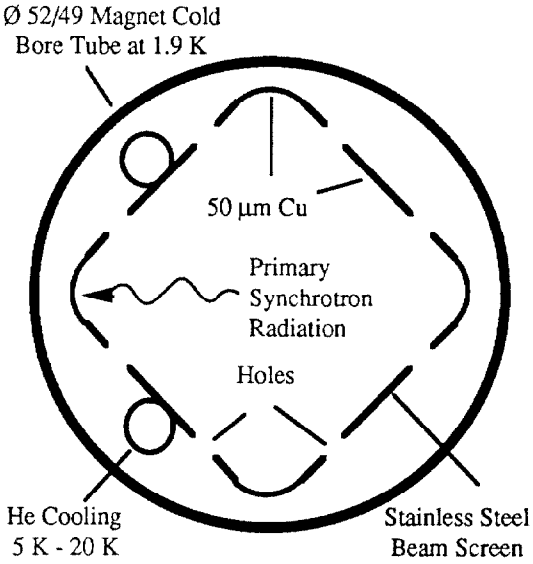

Figure 1. A schematic cross-section of the beam screen in the 1.9 K cold bore tube.

Essentially it will consist of a 1 mm thick stainless steel square section tube perforated with pumping holes over a few percent of its surface area and with a 50 μm layer of pure Cu on the inner surface. The square section optimises the horizontal and vertical apertures available for the beam and the Cu carries the image currents and reduces the coupling impedance. The power from synchrotron radiation and beam image currents will be absorbed by He in the cooling pipes.

3. PHOTON INDUCED GAS DESORPTION

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 [3], [4]. The primary photons are also scattered and reflected, thus producing desorption from all of the screen surface although they initially only strike along a narrow strip one side of the chamber [5].

Photon induced gas desorption yields have been measured at a critical energy of 63.5 eV (close to the 45.4 eV critical energy of the LHC) for an unbaked Cu plated stainless steel

chamber at room temperature. These are shown in Figure 2 as a function of the photon dose [6].

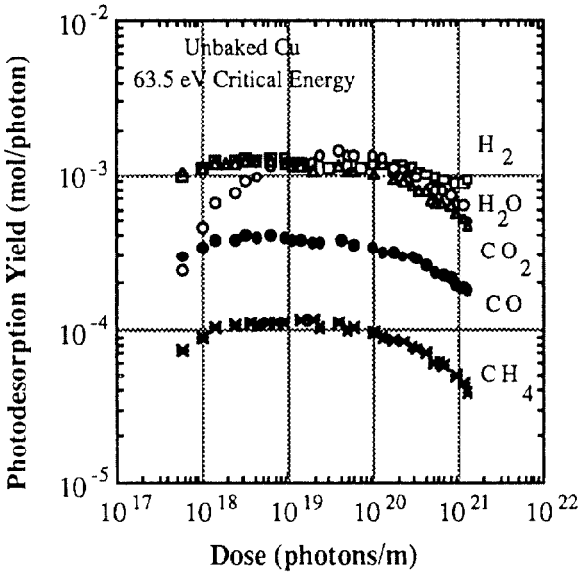

Figure 2. The photon induced gas desorption yields from an unbaked, 100 mm diameter, Cu plated stainless steel chamber as a function of photon dose at 63.5 eV critical energy.

The gases desorbed initially, in order of importance, are H_2, CO_2, CO, H_2O and CH_4. At a dose of 1.25 10^{21} photons/m, which corresponds to 3.6 hours of LHC operation at 7 TeV and 530 mA, all desorption yields were decreasing and showing no signs of levelling off.

Taken together with the photon flux and pumping speeds based on an operating temperature of 10 K with a unit sticking coefficient over the entire inner surface of the screen, these room temperature desorption yields lead to a total equivalent H_2 density of 4.9 10^8 mol cm^{-3} (of which CO_2 contributes 4 10^8 mol cm-3) and a beam lifetime of 188 hours. This lifetime would be largely sufficient, but the estimate is of limited practical value because of the rapid build-up of cryopumped layers and the onset of associated secondary photon desorption and/or thermal vapour pressure.

Recent measurements of photon induced gas desorption yields from Cu plated stainless steel at 4.2 K [7] indicate that the yields, at least for H_2 and CO, are composed of two parts. A primary part for (tightly bound) gas desorbed from the interior or near surface of the oxide layer; this is comparable to the room temperature desorption yield. A secondary part comes from any cryopumped (physisorbed) gas on the surface. The secondary yield from physisorbed H_2 has been observed to increase linearly with coverage and, at one monolayer, to be about a factor of 1000 larger than the yield from the tightly bound gas.

By integration of Figure 2 the total quantity of each gas desorbed was obtained. 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 where a monolayer is considered to contain 1 10^{15} molecules/cm^2.

4. VAPOUR PRESSURE

The cryopumped gas layer will have a vapour pressure which will increase rapidly when the coverage of about one monolayer is approached. H_2 will be particularly important.

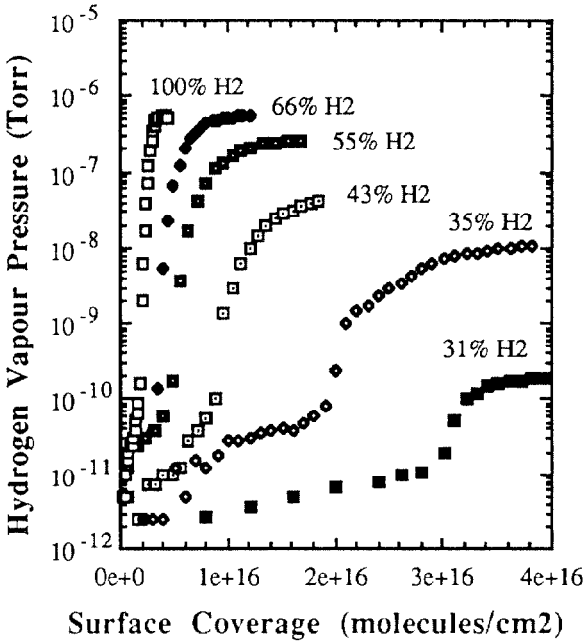

Figure 3. The H_2 vapour pressure of H_2/CO mixtures condensed at 4.2 K as a function of surface coverage.

Figure 3 shows the H_2 vapour pressure resulting from a layer of H_2 and from various mixtures of H_2 and CO adsorbed onto a Cu plated stainless steel surface at 4.2 K [8]. When a surface coverage of about 1 10^{15} molecules cm^{-2} of pure H_2 at 4.2 K is reached the vapour pressure starts to rise steeply and exceeds 7 10^{-7} Torr at a coverage of 3 10^{15} molecules cm^{-2} [9],[10].

However, since the cryopumped layer in LHC will not be composed of a single pure gas but a mixture containing H_2, CH_4, H_2O, CO and CO_2, it is the vapour presure of this composite layer which is relevant. The effect, see Figure 3, of adding different concentrations of CO to an H_2/CO gas mixture is to reduce the H_2 vapour pressure at saturation to about 2 10^{-10} Torr at 31% H_2/69% CO and thus, in principle, enable larger surface coverages to be accumulated for a given increase in the H_2 vapour pressure. At 4.2 K the vapour pressures of CO, CH_4 and CO_2 are negligible. The addition of CH_4 or CO_2 to H_2 has a similar effect [8]. Unfortunately the first indications are that this suppression of the H_2 vapour pressure may not be effective in the presence of synchrotron radiation; this is now being verified in detail.

5. PERFORATED BEAM SCREEN

The major problem with the predicted behaviour of the LHC vacuum system stems from the build-up of the cryopumped gas layer leading to a high secondary desorption and an increasing H_2 vapour pressure. The introduction of distributed pumping holes in the screen will, however, dramatically modify this vacuum behaviour. Suppose that 2% of the screen surface is perforated with holes which communicate to the cold bore at 1.9 K. The holes are assumed to be perfectly gas transparent and perfectly opaque to synchrotron radiation. If the total cryopumping speed of the inner beam screen surface with a unit sticking coefficient is S $ls^{-1}m^{-1}$ then the 2% of holes will have a pumping speed $s=S/50$ $ls^{-1}m^{-1}$.

When the machine is first put into operation the initial pressure will be Q/S Torr where Q (Torr $ls^{-1}m^{-1}$) is the quantity of each gas desorbed by the synchrotron radiation 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 l $s^{-1}m^{-1}$) i.e. it increases as the pressure increases.

If we consider only H_2, then as the H_2 coverage progressively builds up on the beam screen surface the thermal vapour pressure of H_2 will increase and, if there were no holes, it would increase to its saturation value corresponding to the temperature of the screen, e.g. $\sim 10^{-6}$ Torr at 4.2 K. The holes, however, will pump an increasing fraction of the desorbed H_2 and an equilibrium coverage may be reached when the quantity of desorbed gas equals the quantity swallowed by the holes i.e. Q=P.s. The equilibrium pressure of H_2 is therefore given by Q/s which is, for 2% holes, a factor of 50 above the initial H_2 pressure when all of the gas load condenses continually on the 1.9 K surface where its vapour pressure is negligible.

For the other gases the corresponding partial pressures may remain unchanged at Q/S since their saturated vapour presures at the temperature of the beam screen will be insignificant. Should it turn out however, that any of these gases, as already shown for H_2, is strongly desorbed from the condensed layer by synchrotron radiation, then a self-regulating process analogous to that described above for the thermal desorption of H_2 will come into play and again limit the coverage and the equilibrium increase in pressure to a factor of 50 for 2% of pumping holes.

Whereas a factor 50 increase of gas density, with the related reduction of beam lifetime, would be acceptable for H_2 it would be unacceptable for the heavier gases, e.g. if, in particular, CO_2 proves to show a strong secondary desorption. It might then be necessary to run during the initial months of operation at reduced beam current until the accumulated dose gave a sufficient beam clean-up of CO_2, or to warm up the screen periodically to desorb the cryopumped layer. A larger fraction of pumping holes would help, but this is severely restricted by the unwelcome contribution to the beam coupling impedance.

Pumping holes render the temperature and temperature uniformity of the screen relatively unimportant. The temperature only affects the equilibrium coverage on the screen via the adsorption isotherm 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. From vacuum considerations alone the condensing surface of the magnet cold bore could operate equally well 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.

6. CONCLUSIONS

Measurements of the photon induced gas desorption yields from Cu at room temperature have indicated that the gases desorbed have yields between 10^{-3} and 10^{-4} molecules per photon. However, it has also been shown that at 4.2 K the secondary desorption from a monolayer of physisorbed H_2 can dominate the situation with a yield approaching unity.

The effect of cryopumping mixtures of H_2 with CH_4, CO or CO_2 at 4.2 K is to suppress the vapour pressure increase of the H_2 for more time, though possibly only in the absence of synchrotron radiation.

Other effects tending to increase the pressure are due to ion bombardment of the walls by residual gas ions created by the proton beam [11] and electron bombardment driven by the electric field of the proton bunches (multipacting) [12].

It has been shown that the effect of the perforated beam screen is to limit such pressure increases to a value which depends on the initial desorption and the total pumping speed of the perforations

7. REFERENCES

[1] The Large Hadron Collider Accelerator Project (LHC), The LHC Study Group, CERN/AC/93-03(LHC), 8 November, 1993.

[2] B. Angerth, F. Bertinelli, J-C. Brunet, R. Calder, O. Gröbner, A.G. Mathewson, A. Poncet, C. Reymermier, R. Valbuena, European Particle Accelerator Conference, London, England, June 1994.

[3] G.E. Fischer and R. A. Mack, J. Vac. Sci. Technol., 2, 123, (1965).

[4] M. Bernardini and L. Malter, J. Vac. Sci. Technol., 2, 130, (1965).

[5] O. Gröbner, A.G. Mathewson, P. Strubin, E. Alge and R. Souchet, J. Vac. SCi. Technol., A7(2), March/April (1989).

[6] J. Gómez-Goñi, O. Gröbner and A. G. Mathewson, Vacuum Group Technical Note 93-01, February, 1993.

[7] V. Anashin, O. Malyshev, V. Osipov, I. Maslennikov, and W. Turner, Superconducting Super Collider Laboratory Internal Report, SSCL-Preprint-517, October 1993, to be published in J. Vac. Sci. Technol.

[8] E. Wallén, CERN, Private Communication.

[9] C. Benvenuti, R.S. Calder and G. Passardi, J. Vac. Sci. Technol., 13, (1976), 1172.

[10] V. Anashin et al., Superconducting Super Collider Laboratory Internal Report, SSCL-Preprint-533, Nov. 1993, to be published in J. Vac. Sci. Technol.

[11] E. Fischer and K. Zankel, CERN Divisional Report ISR-VA/73-52 (1973).

[12] O. Gröbner, Proc. Workshop on pp bar in the SPS, Geneva 1980 (CERN Divisional Report SPS-pp bar-1, Geneva, 1980), 130.