Dynamic Vacuum in the Beam Tube of the SSCL Collider - Cold Beam Tube and Liner Options*

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Abstract

In this paper model equations are derived for calculating the beam tube density of molecules desorbed by synchrotron radiation in the SSCL 20TeV proton Collider and the supporting simulation experiments at synchrotron light sources. Cold 4.2K beam tube and arbitrary temperature liner or distributed pump systems are considered. Physical effects included are; direct desorption, cryosorption, desorption of physisorbed molecules, the H_2 equilibrium isotherm, axial diffusion and distributed pumping. Convenient formulas are given for extracting the relevant physical variables from the simulation experiments and calculating the anticipated beam tube density in the Collider. A numerical example illustrating the important physical effects is presented.

I. INTRODUCTION

The new generation of proton colliders - SSC and LHC - are the first that will encounter significant synchrotron radiation in the cold bore tube of superconducting magnets. The vacuum systems of such colliders require taking into account the gas desorbed by synchrotron radiation to insure adequate beam lifetime and machine availability. Although the cold magnet bore tube can in principle serve as a cryopump its effectiveness can be limited by two effects. Firstly cryosorbed gas is rather weakly bound to the surface and may be easily desorbed, so the effective pumping speed may be severely reduced. Secondly, in the case of the SSC, the saturation vapor density of H_2 at the 4.2K magnet operating temperature exceeds the cryogenic/magnet quench limit by a factor of fifty, so accumulation of a monolayer of H_2 anywhere in the beam tube must be avoided.[1] The function of a liner is to intercept the photon flux and to pump the photodesorbed gases in a way that shields them from the synchrotron radiation. It will turn out that specifying a liner configuration that will work depends on far less information than qualifying a simple beam tube without a liner, if indeed such a tube exists. The situation with LHC is that because of the low 1.8K magnet operating temperature a 10-20K liner has been designed in from the beginning to intercept the synchrotron radiation heat load.[2] For the SSC it is reasonable to intercept the synchrotron heat load at 4.2K so whether to install a liner is an open question. Furthermore the temperature of the liner could be chosen to correspond to any of the available refrigeration systems 4.2K, 20K or 80K and each choice has its particular advantages and disadvantages.

Some basic synchrotron radiation parameters for the SSC are photon critical energy = 284eV, photon intensity = 1×10^{16}photons/m/s at 20TeV and 72mA and synchrotron power = 140mW/m. The photons hit the vacuum chamber wall at an incidence angle ~2mrad at a distance ~20m from their point of emission on the proton orbit. The FWHM of the directly illuminated stripe on the beam tube wall depends on the photon energy and is ~4mm for the median photon energy $.08E_{crit}$ = 23eV. The vacuum design goals are 300hr beam lifetime due to nuclear scattering and beam tube warm up interval of the order once per operational year (~2×10^{23}photons/m). The 300hr beam lifetime requirement corresponds to an average H_2 density 3×10^{8}/cm^3 or CO density 5×10^{7}/cm^3. The cryogenic limit 0.6W/m[3] corresponds to local density limits 4×10^{10}/cm^3 for H_2 and 7×10^{9}/cm^3 for CO. Accumulation of less than one monolayer of H_2 in an operational year corresponds to an average photodesoption coefficient $\leq 2\times10^{-5}$ H_2/photon.

II. BASIC EQUATIONS

We begin by writing down equations describing the volume density n and surface density s of H_2 inside a 4.2K beam tube of radius a exposed to synchrotron radiation. Some comments on the treatment of other gases (CO,CO_2,CH_4) and tube temperatures (20K, 80K) will be made below. The equation for volume density is;

$$V\frac{\partial n}{\partial t} = \eta_1\dot{\Gamma} + \eta'\dot{\Gamma} - \sigma_W S_W * (n - n_e) - C * n + A_C D\frac{\partial^2 n}{\partial z^2} \qquad (1)$$

In eqn.(1) $V = \pi a^2$ is the beam tube volume per unit axial length. The first two terms on the right describe photodesorption of molecules. The desorption coefficient η_1 molecules per photon is for chemically bound matter not previously desorbed and is a function of the integrated photon flux per unit length Γ and perhaps the photon intensity $\dot{\Gamma}$. The second term allows for the desorption of relatively weakly bound physically sorbed molecules with desorption coefficient η' which is a function of the surface density s of cryosorbed molecules. At low surface coverage one would expect η' depends linearly on the surface density s; $\eta' = \eta_0'\left(\frac{s}{s_m}\right)$ where s has been normalized to the monolayer density s_m. The third term on the right of eqn.(1) accounts for the cryosorption of molecules incident on the surface; σ_W is the sticking probability per wall collision, $S_W = \bar{v}A_W / 4$ is the ideal wall pumping speed and n_e is the equilibrium isotherm density of molecules with surface density s. The fourth term allows for a liner or distributed pump with pumping speed C per unit axial length. The last term allows for the axial diffusion of molecules out the ends of a finite length tube; $A_C = \pi a^2$ is the tube cross section area and $D = \frac{2}{3}a\bar{v}$ is the Knudsen

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diffusion coefficient. The equation for the surface density s of cryosorbed molecules is;

$$A_w \frac{\partial s}{\partial t} = \eta_2 \dot{\Gamma} + \sigma_w S_w * (n - n_e) - \eta' \dot{\Gamma}. \qquad (2)$$

The first term in eqn.(2) allows for the possibility of direct production of physisorbed molecules by the incident photon flux. The second and third terms are the same as in eqn.(1) but with opposite sign. All the terms on the right of eqn.(2) define the effective pumping of the beam tube surface which we note is reduced by the equilibrium isotherm and by the photodesorption or recycling of cryosorbed molecules. One more equation is needed to describe the equilibrium isotherm relating n_e to s. Here we choose to represent the isotherm by a BET equation;

$$x = \frac{\alpha y}{[(1-y)(1+(\alpha-1)y)]} \qquad (3)$$

where $x = s/s_m$ and $y = n_e/n_{sat}$ and $\alpha = e^{\Theta/T}$ is a dimensionless parameter. Eqn.(3) has the saturation property $y \rightarrow 1$ as $x \rightarrow \infty$. For any particular surface the equilibrium isotherm must be measured experimentally to determine s_m and α. Hydrogen isotherms have been measured on stainless steel by Benvenuti et al[4] and the 4.2K isotherm can be reasonably fit with $s_m = 6\times10^{15}$ H_2/cm^3 and $\alpha = 1.37\times10^4$. In ref.[2] the saturation density of H_2 was also determined to be $n_{sat}(cm^{-3}) = 6.84\times10^{22}e^{-95.8/T}/T$. For our purposes s_m, which depends on the particular surface, and n_{sat} are the most important parameters and results are not too sensitive to uncertainty in α.

III. SOLUTIONS

The equations in Sec. II will be applied to tubes of length L with $-L/2 < z < L/2$ and the boundary condition $n(\pm L/2) = 0$ applied at the ends. In practice the density at the ends of a tube will be determined by the gas flow rate and pumping speed, which here we take to be infinite compared to the tube conductance. It is straightforward to add a finite density boundary condition to the solutions given below. Here we are only interested in quasi-static solutions $V\frac{\partial n}{\partial t} \approx 0$ so the time dependence (slow) of n enters through the behavior of the desorption coefficients with increasing photon flux and increasing isotherm density due to the build up of surface density on the beam tube. We characterize the length of a tube without a liner according to whether the surface density reaches a quasi-steady state $A\frac{\partial s}{\partial t} \approx 0$ due to diffusion out the ends or continues to build up due to cryosorption and η_2. Tubes with a surface reaching steady state are deemed to be "short", others "long". We first give the solutions for short and long tubes without liners and then give a criterion for short or long. The solution is then given for an arbitrary length tube with a liner. The presence of liner pumping again allows the surface to reach a quasi steady state $A\frac{\partial s}{\partial t} \approx 0$.

A. Short 4.2K beam tube without a liner

The solution to eqn.(1) for density n(z) with $V\frac{\partial n}{\partial t} \approx 0$, C = 0 and $A\frac{\partial s}{\partial t} \approx 0$ is;

$$n(z) = \frac{1}{2}\frac{(\eta_1+\eta_2)\dot{\Gamma}}{A_c D}\left(\frac{L}{2}\right)^2\left[1 - \frac{z^2}{\left(\frac{L}{2}\right)^2}\right]. \qquad (4)$$

Given the density n(z), the surface density s(z) is obtained by solving the following implicit equation for s;

$$\eta'(s) = \eta_2 + \frac{\sigma_w S_w}{\dot{\Gamma}}(n(z) - n_e(s)). \qquad (5)$$

If $n_e << n(z)$ and $\eta_2 << \eta'(s)$ then

$$\eta'(s) = \frac{\sigma_w S_w}{\dot{\Gamma}} n(z). \qquad (6)$$

If we make the further substitution $\eta' = \eta_0'\left(\frac{s}{s_m}\right)$ the surface density is given explicitly by

$$s(z) = \left[\frac{\sigma_w S_w}{\eta_0'\dot{\Gamma}} n(z)\right] s_m. \qquad (7)$$

We note that the diffusion out the ends of the tube is driven by isotherm evaporation and η' desorption. If there is no η' process then isotherm evaporation alone drives the diffusion and s is given implicitly by;

$$n_e(s) = n(z) + \frac{\eta_2 \dot{\Gamma}}{\sigma_w S_w}. \qquad (8)$$

B. Long 4.2K beam tube without a liner

The solution to eqn.(1) for n(z) with $V\frac{\partial n}{\partial t} \approx 0$, C = 0 and $A\frac{\partial s}{\partial t} \neq 0$ is;

$$n(z) = \left[\frac{\eta_1\dot{\Gamma}}{\sigma_w S_w} + \frac{\eta'\dot{\Gamma}}{\sigma_w S_w} + n_e\right] x \left[1 - \frac{\cosh\left(\frac{z}{\lambda}\right)}{\cosh\left(\frac{L}{2\lambda}\right)}\right] \qquad (9)$$

where $\lambda^2 = \frac{A_c D}{\sigma_w S_w} = \frac{4}{3}\frac{a^2}{\sigma_w}$ and we neglect possible z dependence of η' and n_e. The mean square axial distance a molecule travels before sticking to the wall is $2\lambda^2$ and L^2/λ^2 is equal to the wall pumping speed divided by the conductance of a tube of length L. Evidently as long as we are a few tube diameters from the end of the tube the cosh term is negligible and we have;

$$n = \frac{\eta_1\dot{\Gamma}}{\sigma_w S_w} + \frac{\eta'\dot{\Gamma}}{\sigma_w S_w} + n_e \qquad (10)$$

which is the solution obtained with axial diffusion neglected, $A_c D\frac{\partial^2 n}{\partial z^2} \approx 0$. Inserting eqn.(10) into eqn.(2) we obtain for the surface density;

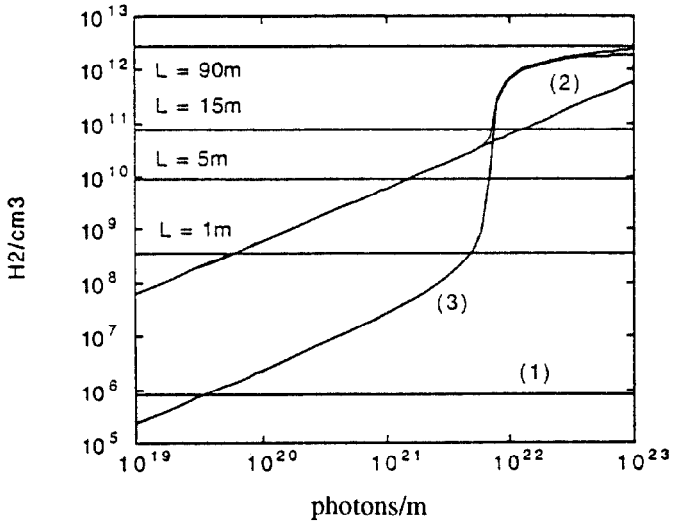
$$s = \frac{1}{A_w}\int_0^{\Gamma}(\eta_1 + \eta_2)d\Gamma \qquad (11)$$

which just says all the desorbed gas winds up on the surface.

C. Numerical example for 4.2K beam tubes

In this section we give an example to illustrate the content of the equations. The measurement of a complete set of parameters at 4.2K is incomplete so we take the following assumed values: $\eta_1 = \eta_2 = 4\times10^{-4}$, $\eta_0' = 10$, $\sigma_w = 0.5$, $\bar{v} = 2.1\times10^4\, cm/\sec$, a = 1.5cm, $s_m = 3\times10^{15} H_2/cm^2$, $\alpha = 1.3\times10^4$ and $\dot{\Gamma} = 10^{16}$ photons/m/sec. The short tube solution eqn.(4) depends on the tube length which we take to be L = 1, 5, 15 and 90m. These lengths correspond approximately to: a typical beam tube sample for photodesorption experiments, a Collider quadrupole magnet or spool piece, a Collider dipole magnet and a Collider half cell. The long tube solution eqn.(10) depends on the integrated photon flux which we take to be $\Gamma = 1\times10^{19}$ to 1×10^{23} photons/m, corresponding to 1000sec to 100days of Collider operation. The long tube solution is independent of length and is plotted versus Γ in Fig. 1. The three components of the long tube solution are also shown: (1) the η_1 term, (2) the η' term and (3) the isotherm. The short tube solutions are independent of Γ and are indicated by the horizontal lines in Fig. 1 that are labeled with L = 1, 5, 15 and 90m. For a given tube length it is the lower density of the long and short tube solutions which pertains. For this reason one always starts out at low Γ on the long tube solution and follows it until it intercepts the short tube solution for the chosen length.

Fig.1:Short and long tube H_2 density



From the results in Fig. 1 we make several observations for the assumed parameters. The long tube solution is dominated by the η' desorption of cyrosorbed H_2, which increases linearly with Γ, until the isotherm density takes over at $\Gamma \sim 8\times10^{21}$ photons/m. The η desorption of H_2, which drives everything, dominates the density only at very low accumulated photon flux not shown in Fig. 1. We also see that L = 1 and 5m tubes reach maximum densities of 3.4×10^8 and 8.4×10^9 due to pumping at the ends and do not reach the region of rapid rise due to the isotherm. The relevance of this is that short tube photodesorption experiments at synchrotron light sources with tube lengths 1 to 5m may not observe the rapid isotherm density rise although the parameters may be the same as those which would lead to such a rise in a much longer tube. The 15m tube reaches the region of rapid isotherm rise, but pumping at the ends clamps the density at 7.6×10^{10} H_2/cm^3. The 90m case reaches the isotherm saturation region before intercepting the short tube solution. For the particular parameters chosen, pumping at the ends of a 5m long quadrupole or spool piece would keep the density from reaching the value 4×10^{10} H_2/cm^3 which would lead to a beam loss induced cryogenic overload/magnet quench, but fall short for a 15m dipole by a factor of two. Pumping at 1m intervals would be required to keep the density at the 300hr beam lifetime goal level of 3×10^8 H_2/cm^3.

D. Beam tube length criterion

In this section we summarize a criterion for whether to usé the long or short tube solutions to calculate n(0). For a given set of parameters calculate n(0) using the long tube solution eqn. (10). Then evaluate the expression;

$$S = \frac{16\pi}{3}\frac{a^2}{L^2}\frac{n(0)\bar{v}a}{\eta\dot{\Gamma}}. \qquad (12)$$

If $S \le 1$, use the long tube eqn.(10), if $S > 1$ use the short tube eqn.(4).

E. Beam tube with a liner

The case of a beam tube with a liner is only interesting when $Cn >> A_c D\partial^2 n/\partial z^2$. In that case, and with the quasi static approximations $V\frac{\partial n}{\partial t} \approx 0$ and $A\frac{\partial s}{\partial t} \approx 0$, the solution to for the density is;

$$n = \frac{(\eta_1 + \eta_2)\dot{\Gamma}}{C}. \qquad (13)$$

The solution for the surface density is the same as eqns.(5) to (8). Eqn.(13) is remarkable in its simplicity compared to eqn.(10). It depends only on the desorption coefficient $\eta = \eta_1 + \eta_2$ to specify a conductance C that will meet the beam lifetime criterion. Eqn.(13) is valid for any temperature liner and is independent of whether on not there is cryosorption on the liner surface. The conductance C is related to the holes in the liner by $C = pN_hA_h\bar{v}/4$ where p is the transmission probability, N_h the number of holes per unit axial length, A_h the area per hole and $\bar{v}$ the mean molecular speed. Although the mean speed $\bar{v}$ may be higher than that corresponding to equilibrium with the liner, a conservative estimate of the conductance may be made by assuming the molecules and liner are in thermal equilibrium. When using eqn.(13) to estimate the conductance it is important to include desorption of all the molecules since the heavier molecules have slower speeds and higher scattering cross sections. The calculational details cannot be given here, but at present it seems possible to specify liners with T = 4.2, 20 or 80K which will meet the 300hr beam lifetime requirement with an effective open hole area of ~ 3%. This is small enough to allow a comfortable safety margin for tranverse beam instabilities.

IV. REFERENCES

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