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Beam Tube Vacuum in Low Field and High Field Very Large Hadron Colliders*

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ABSTRACT

Bounds on the beam tube gas pressure and the required pumping speed are estimated for ~ 2 T low field (LF) and ~ 12 T high field (HF) 100 TeV center-of-mass hadron colliders. In both cases photodesorption by synchrotron radiation is the dominant source of gas. Assuming beam-gas scattering limited luminosity lifetime five times the IP scattering lifetime, the required CO equivalent beam tube pressure is 0.25 nTorr for LF and 1.8 nTorr for HF, ambient room temperature equivalent. The CO equivalent pumping speeds required to achieve this pressure within a reasonable beam conditioning time (a few tenths of an operational year at design intensity) are estimated to be ~ 300 l/s-m for LF and ~ 40 l/s-m for HF. For the LF case with a superferric warm iron magnet, the beam tube is at ambient room temperature and a distributed NEG plus lumped ion or cryo pump system is considered. The size of antechamber needed, ID ~ 6 cm, requires that it be located outside the ~ 2 cm C-coil magnet gap. Lumped pumps for pumping CH_4 need to be spaced at ~ 20 m intervals on the antechamber. For the HF case the likely beam tube temperature is 15-20 K and cryopumping with a beam screen system is considered. The necessary pumping speed can be achieved with slots covering ~ 2 per cent of the beam screen surface.

I. INTRODUCTION

In this paper we will discuss beam tube vacuum in low field (LF) and high field (HF) very large hadron colliders. The emphasis will be on establishing firstly how low the beam tube vacuum must be and secondly how much pumping speed is needed to reach the desired pressure in a reasonable conditioning time. Some assessment will then be made of the practicality of achieving the needed pumping speeds in the machines that are under discussion.

The parameters necessary for evaluating beam tube vacuum are summarized in Tables I and II for 50+50 TeV LF and HF hadron colliders. Further discussion of these machines and the rational for the choice of parameters may be found in Ref. [1]. From the viewpoint of beam tube vacuum the first things to notice in Table I are: (1) the small apertures, to minimize the cost of the magnets but still achieve acceptable field quality, (2) the difference in the likely beam tube temperatures and (3) the particle lifetimes due to pp collisions at the interaction points (IP). For the LF version the double C superconducting transmission line superferric magnet has an ambient room temperature iron yoke [2]. The beam tube is also at room temperature T_w ~ 294 K and is racetrack or elliptical in cross section with semi-axes 0.75 cm and 1.5 cm. The C magnet geometry is an important feature because it allows the possibility of locating the pump antechamber outside the magnet. Discussions of magnet options for the HF version are considerably more varied than for LF however they all share the characteristic of a beam tube surrounded by superconductor and cryostat either in cos(θ) or block coil construction. The beam tube inside radius has been specified as r_w = 1.65 cm. The temperature of superconductor discussed runs from 1.8 K NbTi to 4.5 K Nb_3Sn to high temperature superconductor ~ 4 - 30 K. In order to avoid absorbing synchrotron radiation at the lowest temperatures but also to allow for cryopumping H_2 the most likely beam tube temperature is T_w ~ 15-20 K for all cases. The proton lifetimes determined by pp collisions at the IP are 130 hrs for LF and 32 hrs for the HF collider. The lifetime due to beam-gas collisions should be much longer and this sets the bounds on beam tube pressure that are discussed in Sec. II.

Table I: Initial parameters for low and high field hadron colliders.

Parameter	LF	HF
E_b, TeV	50	
B, T	1.8	12.6
C, km	646	104
M	129,240	20,794
N_p	0.94×10^{10}	0.5×10^{10}
I_b, mA	90	48
β, m	255	
ε_n, π mm-mrad	1	
r_w, cm	0.75x1.5	1.65
T_w, °K	~ 294	~ 15-20
τ_p, hrs	130	32

Synchrotron radiation parameters are given in Table II. Since photodesorbed gas is the dominant gas source in the beam tube, photon intensity is the most important parameter for beam tube vacuum, 0.34×10^{16} ph/m-sec for LF and 1.26×10^{16} ph/m-sec for HF. The magnitude of pumping speed required to remove photodesorbed gas is estimated in Sec. III. The photon intensity for the LF and HF hadron colliders is much less than present day high current electron-positron storage rings so one might think pumping the hadron machines is relatively trivial. For example the 9 GeV, 1 A PEPII high energy electron ring (HER) at SLAC has

$\dot{\Gamma} = 7.1\times10^{18}$ ph/m-sec [3]. In fact, because photodesorption coefficients decrease with integrated photon intensity Γ, the electron machines clean up much faster than the hadron machines. It turns out that the pumping speeds, or more accurately the pumping apertures, needed for the LF and HF colliders are the same order of magnitude as for the PEPII HER. For both LF and HF hadron colliders the photon critical energy E_c is low enough that the synchrotron radiation is absorbed in the beam tube and no special shielding is needed outside the beam tube. The synchrotron radiation power in the LF collider, 0.082 W/m, is absorbed at room temperature and is low enough that no cooling loop is needed. The synchrotron radiation power for the HF collider is absorbed at T_w ~ 15-20 K and will need a cryogenic refrigeration loop to remove it. The radiation damping time for the LF machine is 114 hrs and longer than the luminosity lifetime τ_L = 65 hrs whereas radiation damping is only 2.6 hrs in the HF machine and much less than the luminosity lifetime τ_L ~ 16 hrs. Consequently, for LF we must consider beam-gas scattering by two processes: (1) single proton-nuclear collisions leading to a lost proton and (2) multiple small angle proton-nuclear Coulomb collisions leading to increase in emittance. Only particle loss by a single proton-nuclear collision need be considered for HF.

Table II: Synchrotron radiation related parameters.

Parameter	LF	HF
$\dot{\Gamma}$, ph/m-sec	0.34×10^{16}	1.26×10^{16}
E_c, keV	0.48	3.4
$P/2\pi\rho$, W/m	0.082	2.12
P, kW	47.5	176.6
ΔE, MeV/turn	0.53	3.7
τ_D, hrs	114	2.6

For purposes of numerical estimates in this report we will always use the initial values of machine parameters given in Tables I and II. The case of emittance in the HF machine is somewhat involved because the value given in Table I is an initial value and not an equilibrium one. The emittance will damp to an equilibrium value in a few radiation damping times. This complication is ignored here. Where needed we will simply take emittances from Table I and define numerical values of the luminosity lifetime due to pp collisions at the IP as $\tau_L = \tau_p/2$; so τ_L = 65 hrs for LF and τ_L = 16 hrs for HF. The lifetime characterizing loss of luminosity due to beam-gas collisions should be long compared these estimates of τ_L.

II. BOUNDS ON BEAM TUBE GAS PRESSURE

Assuming the LF and HF colliders are not operating at the beam-beam tune shift limit, the luminosity lifetime τ_L is related to the particle loss time τ_p and emittance growth time τ_ε (< 0 if there is net damping) by $1/\tau_L = 2/\tau_p + 1/\tau_\varepsilon$. For purposes of characterizing beam tube vacuum we define the luminosity loss rate $1/\tau_g$ due to beam gas scattering in an analogous manner with $1/\tau_p$ being the proton loss rate due to collisions with gas nuclei and $1/\tau_\varepsilon$ the emittance growth rate due to multiple Coulomb scattering. Proton collision cross sections σ_{pj} per molecule and radiation lengths X_{0j} are listed for the gases of interest in Table III. A convenient formula for calculating τ_g in terms of the circumferentially averaged pressures of the various gases is;

$$\frac{1}{\tau_g(hrs)} = 7.2\times10^{-6}\sum_j \sigma_{pj}(mb)\bar{P}_j(nTorr) + \frac{1.33\times10^{-6}\gamma\beta(m)}{cp(TeV)^2\varepsilon_n(\pi\, mm-mrad)}\sum_j \frac{A_j(gm)\bar{P}_j(nTorr)}{X_{0j}(gm/cm^2)} \quad (1)$$

where A_j is the gram molecular weight, γ is the relativistic factor E_b/m_pc^2 and $\beta(m)$ is the lattice beta function in Table I, not to be confused with v/c. The first term in Eqn. 1 is twice the proton loss rate and the second is the emittance growth rate. For the HF case we drop the second term because the radiation damping time is much shorter than the luminosity lifetime, $\tau_D << \tau_L$, whereas for the LF case we keep both terms because $\tau_D > \tau_L$.

Table III: Numerical bounds on beam tube gas pressure.

gas	σ_{pj} (mb)	X_{0j} (gm/cm^2)	$\bar{P}_j$ (nTorr)[a] ($\tau_g = 5\tau_L$)		P_j(nTorr)[a] (0.1 W/m)	
			LF	HF	LF	HF
H_2	120	63	2.8	14.6	56.1	105
CH_4	650	47	0.43	2.7	10.3	19.4
H_2O	690	36	0.36	2.5	9.7	18.3
CO	1000	38	0.25	1.8	6.7	12.6
CO_2	1600	36	0.15	1.1	4.2	7.9

[a] Ambient room temperature equivalent pressure.

The degradation of luminosity lifetime by beam-gas collisions will be negligible if $\tau_g >> \tau_L$; for purposes here we define negligible by $\tau_g > 5\tau_L$ with τ_L = 65 hrs for LF and 16 hrs for HF. The beam tube gas pressures calculated from Eqn. 1 for $\tau_g = 5\tau_L$ are given in Table III for each gas species taken separately. From Table III we see that the CO scattering equivalent beam tube pressure for $\tau_g > 5\tau_L$ must be less than 0.25 nTorr for LF and less than 1.8 nTorr for HF. The pressures given in Table III are ambient room temperature (294 K) equivalent, so density is obtained by multiplying by 3.3×10^{16} molecules/Torr regardless of beam tube temperature. The room temperature equivalent pressure bound for the LF collider is 7.2 times less than for the HF collider; a factor of four is due to the longer luminosity lifetime for the LF collider and the remaining factor of approximately two is due to inclusion of beam-gas scattering emittance growth in the LF case.

In addition to degradation of luminosity lifetime, a second consideration of beam-gas scattering is the scattered beam power. The energy carried by the scattering products is dominated by deeply penetrating particles that pass through the beam tube. Some of this power gets absorbed in the magnet cryostat, and must be allowed for in the overall heat budget, and some is absorbed in the superconducting cable, and if high enough can cause a magnet quench. For the HF case with the magnet iron surrounding the beam tube most of the scattered beam power can be expected to be absorbed in the superconductor and the magnet iron and, if the iron is cold, in the magnet cryostat. The LF case is different. Owing to the C-coil structure significant beam scattered power will leave the magnet structure in the horizontal plane. Furthermore the magnet iron is warm so heat deposited in it does not have to be removed by the cryogenic system. However the superconducting transmission line lies in the horizontal plane between the two beam tubes and will absorb some fraction of scattered beam power. Usually consideration of luminosity lifetime sets a lower bound on the circumferentially averaged beam tube pressure than consideration of the scattered beam power deposited in the magnet cryostat. However the cryogenic heat load of scattered beam power can be a concern for early accelerator operation, before the beam tube has cleaned up sufficiently to meet the luminosity lifetime goal. Also beam power scattered by local pressure bumps, such as would occur after replacement of a component in an otherwise conditioned ring, could exceed the quench limit without having a noticeable effect on the circumferentially averaged beam tube pressure. Detailed radiation deposition calculations have not yet been done for the LF and HF magnets so in Table III, to give an idea of the magnitude of the effect, we simply give the beam tube pressure of each gas species that would result in a scattered beam power 0.1 W/m. This corresponds to a typical global bound for the cryogenic refrigeration plant and conventional $\cos\theta$ magnets using today's technology; a local quench bound would typically be ten times higher, again for conventional $\cos\theta$ magnets. A convenient formula for calculating the beam gas scattered beam power is;

$$P'(W/m) = 3.3\times10^{-9} I_b(mA) E_b(TeV) \times \sum_j \sigma_{pj}(mb) P_j(nTorr) \qquad (2)$$

III. PUMPING OPTIONS

In principle for the LF option distributed non-evaporable getters (NEG), distributed ion pumps (DIP), distributed titanium sublimation (TSP) and distributed cryopumps could all be used in an antechamber configuration connected to the beam chamber with slots. The getter options would need to be supplemented with lumped ion or cryo pumps to pump methane. These would be connected to the antechamber at an axial interval discussed in Sec. IV below. The distributed cryopump option has some attraction if it could be incorporated with the cold gas return for the superconducting transmission line; no lumped pumps and no activation are needed. However it adds the complexity of heat shields and cryogenic penetrations into the antechamber. A NEG concept similar to LEP [4] has been discussed by Ishimaru [5] with some adaptations to the present situation. It has the merit of relative simplicity, a single NEG strip running inside the antechamber, but needs significant lumped pumping for methane and cooling during activation and reconditioning. Distributed ion pumps in the form of stacked perforated plates in an antechamber as in the PEPII HER [6] are a possibility but the size of system needed would place it outside the double C iron yoke so the ion pumps would need their own magnets and could not run parasitically off the bend magnetic field. Although cost comparisons of these systems haven't been done it seems likely that the NEG approach with lumped ion pumps would be the most cost effective.

For the HF option with the beam tube entirely surrounded by cryostat the only option is cryopumping with a beam screen configuration to shield the cryosorbed gases from the synchrotron radiation, similar to LHC[7]. If the magnet cryostat temperature is below ~10 K the beam screen would probably be thermally isolated from the magnet bore tube to allow absorbing the synchrotron radiation at a higher temperature. A beam screen cooling loop would be needed to remove the radiation heat load at ~ 10-20 K. If the magnet cryostat is above ~ 3 K the saturated isotherm pressure of H_2 is too high for accelerator operation and it is necessary to add cryosorber material to increase the effective surface area and prolong the time to reach saturation. For a cryostat ~ 10 K the beam screen and magnet bore tube could be run at the same temperature, and could be a co-extruded structure as discussed by Chou [8]. For temperatures above ~ 15 to 20 K, the precise temperature isn't known, cryopumping will cease to work effectively for H_2 beyond a fraction of a monolayer and the beam screen will again need a cooling loop, this time to keep it cooler than the magnet. We thus have the somewhat paradoxical situation that if high temperature T > 20 K superconducting magnets become a reality for accelerators, they will need a cold T < 20 K insertion for pumping the beam tube.

IV. PUMPING SPEED, CONDITIONING TIME AND BEAM LIFETIME

From Table III we have an estimate of the beam tube pressure that is needed for beam-gas scattering to have a small impact on luminosity lifetime. In this section we will estimate the pumping speed necessary to achieve this pressure within a reasonably short conditioning time. By "reasonably short" we mean a few tenths of a year of operation at design intensity with an operational year being ~ 10^7 sec. So we look for the pumping speed needed to reach $\tau_g > 5\,\tau_L$ by I*t ~ 75 A-hrs for LF and I*t ~ 40 A-hrs for HF. The precise magnitude of a "reasonably short" conditioning time is a matter of some debate. Most would probably agree with our definition within a factor of two and this range of precision is in the spirit of the estimates we are making.

For each gas species "j",

$$S_j P_j = Q_{j,psd} + Q_{j,tsd} \qquad (3)$$

where S_j is the pumping speed, $Q_{j,psd}$ is the photodesorbed gas source and $Q_{j,tsd}$ is the thermally desorbed gas. The photodesorbed gas is related to the photon intensity and photodesorption coefficient η_j by

$$Q_{j,psd}(nTorr-l/s-m) = 3.03\times10^{-11}\eta_j\dot{\Gamma}(ph/m-s) \qquad (4)$$

where the numerical factor converts molecules to Torr-l. The photodesorption coefficients are obtained from experiment [9] and are functions of the integrated photon dose Γ. The η_j can be adequately fit with a simple power law dependence;

$$\eta_j = \eta_{0j}/(\Gamma/\Gamma_0)^{\nu_j} \qquad (5)$$

where the integrated photon flux Γ is related to the A-hrs of beam current by;

$$\Gamma(ph/m) = 2.35\times10^{17}\frac{\gamma}{\rho(km)}I*t(A-hrs). \qquad (6)$$

If we define the pumping speed of species "j" relative to CO by $S_j = f_j{*}S_{CO}$ and substitute Eqn. 3 into Eqn. 1 we obtain the relationship between S_{CO} and τ_g given by Eqn. 7. The magnitude of the right hand side of Eqn. 7 is a function of the integrated photon flux Γ or, from Eqn. 6, I*t. As with Eqn. 1 both summations are retained for the LF case and the second summation is dropped for HF.

$$\frac{S_{CO}(l/m-s)}{\tau_g(hrs)} = 7.2\times10^{-6}\sum_j \frac{\sigma_{pj}(mb)Q_j(nTorr-l/s-m)}{f_j} + \frac{1.33\times10^{-6}\gamma\beta(m)}{cp(TeV)^2\varepsilon_n(\pi mm-mrad)}\sum_j\frac{A_j(gm)Q_j(nTorr-l/s-m)}{f_jX_{0j}(gm/cm^2)} \qquad (7)$$

The CO equivalent pumping speed required to achieve a gas scattering loss time τ_g is plotted versus I*t in Figs. 1 and 2 for the LF and HF cases respectively. The parameters needed for this evaluation are summarized in Table IV. The photodesorption coefficients defined in Eqn. 5 have been fit to the data in Ref. [9], obtained for Al at critical energy 3 keV. This same data should be adequate for LF and HF cases since the dependence of photodesorption coefficients on critical energy is rather weak between 0.5 and 3 keV [10]. Thermal desorption data have been reported for Al vacuum baked in situ at 150 C for 24 hrs [11]. The baking removes water vapor and after that the thermal outgassing rates are very small compared to photodesorption for the time scale of interest here. For the LF case the pumping speeds relative to CO, excluding CH_4, are taken from LEP data utilizing a NEG beam tube vacuum system [12]. For CH_4 the relative pumping speed is varied until it has a noticeable effect and then the supplementary pumping speed by lumped ion pumps is estimated. For the HF case cryopumping is assumed and the f_j coefficients have been taken to be equal to the ratios of the molecular speeds.

Table IV: Numerical values of parameters used for evaluation of Figs. 1 and 2.

gas	η_{0j}*	ν_j	$Q_{j,tds}$ (nTorr-l/s-m)	f_j LF	f_j HF
H_2	.035	0.8	1.61	1.1	3.74
CH_4	.0032	1.25	.016	.005	1.32
CO	.005	0.8	.032	1	1
CO_2	.008	0.8	.032	1	0.8

* For $\Gamma_0 = 10^{20}$ ph/m.

From Fig. 1 we conclude that a pumping speed S = 270 l/s-m is required to reach a beam gas scattering lifetime $\tau_g = 5\tau_L$ at I*t = 75 A-hrs for the LF collider. From Fig. 2 the analogous result for the HF collider is S = 42 l/s-m at I*t = 40 A-hrs. A factor ~ 6.4 less pumping speed is required for HF compared to LF but the effective pumping aperture required differs by a smaller factor of 6.4/4.4 = 1.5 owing to the different molecular velocities at T = 15 K and 294 K.

To assess the feasibility of the pumping speed estimate for the LF case we note that the LEP NEG pumping system achieves a peak pumping speed following conditioning of 500 l/s-m with a 3 cm wide NEG ribbon in a 5 cm x 7 cm antechamber coupled to the beam tube with a 7 mm slot. We conclude that the pumping speed required for the LF case can be achieved provided the antechamber is located outside the 2 cm magnet gap. It does not seem reasonable to reduce the size of the antechamber so that it fits in the magnet gap and at the same time achieve the required pumping speed.

For the HF case we assume a transmission probability 0.7 for molecules passing through slots to the region where they are cryopumped. A pumping speed 42 l/s-m then requires a slot area 22.6 cm^2/m, or equivalently the slots perforate 2.2% of the wall area of a 1.65 cm radius tube. This is reasonable to achieve and in the range discussed for LHC pumping slots [7].

We return now to a few comments regarding the LF case. If a NEG system is used, the pumping speed decreases as molecules accumulate on the surface until the NEG is regenerated and regains its maximum pumping speed. For this reason and because the photodesorption coefficients decrease with the ~ 0.8 power of the integrated photon flux, the actual pumping speed will tend to follow a line of constant τ_g/τ_L in

Fig. 1 until the NEG is regenerated and then jump up to a new line. The calculations in Fig. 1 were done assuming lumped ion or cryo pumps for pumping CH_4, with a fixed pumping speed relative to CO, $f_{CH4} = S_{CH4}/S_{CO} = .005$. The CO pumping speed 270 l/s-m then implies a pumping speed 1.35 l/s-m for CH_4 supplied by lumped pumps attached to the antechamber. The effective pumping speed of the lumped pumps will be conductance limited by the beam tube and antechamber and given by;

$$S_{eff}(l/s-m) = 12\frac{C_L(l/s)}{L(m)} \qquad (8)$$

where L is the distance between lumped pumps and C_L is the axial conductance of the antechamber and beam tube. If the lumped pumps are located only at the L ~ 250 m half cell length, as has sometimes been mentioned, the cross section of the antechamber would need to be ~ 30 cm x 30 cm which seems impractical. If the lumped pumps are located every L ~ 20 m the cross section is reduced to ~ 6 cm x 6 cm which seems reasonable.

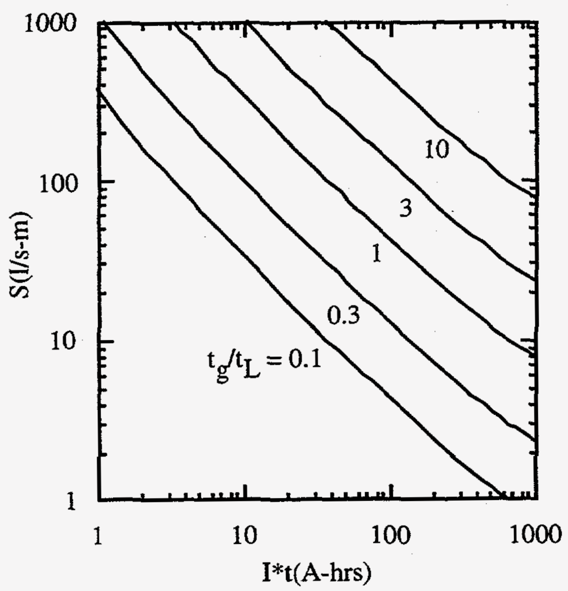

Fig. 1: The pumping speed required to achieve a specified gas scattering luminosity lifetime versus I*t for the LF version of the RLHC. The gas scattering luminosity lifetime τ_g is normalized to the IP luminosity lifetime τ_L = 65 hrs. Beam tube conditioning is expressed in A-hrs, 1 A-hr = 1.36×10^{20} photons/m.

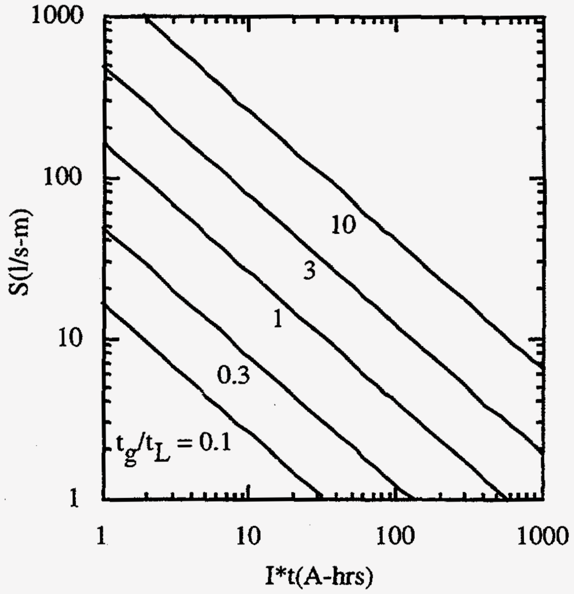

Fig. 2: The calculation in Fig. 1 repeated for the HF version of the RLHC. 1 A-hr = 9.45×10^{20} photons/m.

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