Vacuum Requirements for LAMPF II

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by

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ABSTRACT

The LAMPF II accelerator will require sufficient vacuum to prevent beam loss or beam blowup within the time the beam is in the accelerator. Because this time is quite short ($\tau < 0.03$ s), the vacuum requirements should be somewhat less strict than for the long-time storage machines, such as the ISR ($\tau \gtrsim 10^5$ s). In this note, we catalog various vacuum limitations for LAMPF II and outline vacuum-system parameters that meet these limitations. The pressure $P \lesssim 10^{-7}$ T should be adequate for LAMPF II, and a fairly simple vacuum system should obtain $P \lesssim 10^{-8}$ T.

I. VACUUM LIMITATIONS

A. Nuclear Scattering

Beam particles can scatter against the nuclei of residual atoms in the vacuum chamber, and these particles will be lost. The equation for these losses is

$$\frac{dI}{dt} = -c n I \quad , \quad (1)$$

where I is the beam current, n is the gas atom density, σ is the gas-proton cross section, and $c = 3 \times 10^8$ m/s is the speed of light. With $\sigma \approx 50A^{2/3}$ mb ≈ 300 mb (0.3×10^{-28} m²) for nitrogen and carbon monoxide, (the most common residual gas molecules) and

$$n = 7.04 \times 10^{22} P \text{ (torr) m}^{-3} \quad (2)$$

and the requirement that there be $\lesssim 10^{-3}$ losses in ~ 0.03 s, we find

$$P \lesssim 5 \times 10^{-5} \text{ torr} \quad (3)$$

is required.

B. Coulomb Scattering

Beam collisions with electrons in the residual gas atoms do not lead directly to particle loss but do lead to growth of rms beam size or transverse emittance. From Guignard¹, we obtain the formula

$$\frac{d}{dt} \langle x^2 \rangle = \frac{2K \bar{\beta}_y \beta n_{ms}}{p^2}, \quad (4)$$

where $n_{ms} = 7.05 \times 10^{22} P(T) m^{-3}$ is the atom density, $\bar{\beta}_y \cong 10$ m is the average betatron function, $K = 1.085 \times 10^{-23}$ (for N_2), $\beta = v/c \cong 0.84$, and $p = 1.46$ GeV/c at injection. We find

$$\frac{d\langle x^2 \rangle}{dt} = 135 P(T) \frac{m^2}{s}. \quad (5)$$

If we require $\Delta \langle x^2 \rangle \lesssim (2 \text{ mm})^2$ at 0.03 s, we find

$$P \lesssim 3 \times 10^{-6} \text{ torr} \quad (6)$$

is desired.

C. Beam-Induced Desorption

Beam-gas collisions will ionize gas atoms that will collide with the vacuum-chamber walls, producing further gas atoms. The process is very important at the CERN ISR accelerator because it does limit beam current. The gas production must not exceed gas removal by conduction and pumping, resulting in a criterion, see Eq. 23,

$$\sigma_{\text{Inn}} < C \lambda_v^2 . \quad (7)$$

In Sec. II, we define parameters for Eq. (7) and show conditions where the equation is satisfied.

D. Electron (Ion) - Proton Oscillations

Ionization of gas will produce charged electrons and ions within the vacuum chamber. Oscillations of these charges within the potential well of a coasting proton beam will lead to partial neutralization of the proton space charge and possibly to unstable transverse oscillations. Based on ISR experience, Reich et al.³ present a stability criterion. They demand that the relative neutralization α be less than some threshold

$$\alpha_{\text{th}} = \frac{1}{2.8 B_f \alpha^2} \left(\frac{H_{\text{max}} - H_{\text{min}}}{H} \right) \cong 0.20 \quad (8)$$

at LAMPF II injection with a neutralization rate $\dot{\alpha} \cong 6.0 \times 10^8$ P(T) and a requirement at injection over time T_{inj} ($\cong 0.003$ s) that

$$\dot{\alpha} T_{\text{inj}} < 2\alpha_{\text{th}} , \quad (9)$$

we find a LAMPF II requirement

$$P \lesssim 2 \times 10^{-7} \text{ torr} . \quad (10)$$

More detailed study is desirable to insure that this criterion does indeed insure stability.

II. VACUUM REQUIREMENTS

Our model for the vacuum system is an elliptical beam pipe (of cross section 5 by 10 cm) with pumps spaced a distance $2L$ apart (see figure). The vacuum within the chamber can be represented by the solution of the equation²

$$A \frac{\partial n}{\partial t} = g + \sigma I \eta n + C \frac{\partial^2 n}{\partial x^2} , \quad (11)$$

where $n(x,t)$ is the gas molecular density. The pumps are represented by a boundary condition at $x = \pm L$

$$\left[C \frac{\partial n}{\partial x} \pm S n \right]_{x = \pm L} = 0 . \quad (12)$$

In these equations, $2S$ is the "pumping speed" [237 ℓ/s for Proton Storage Ring (PSR) pumps], and C is the "conductance" of the vacuum pipe per unit length. In Eq. (11), g is the outgassing rate per unit length of the vacuum pipe, and A is the cross-sectional area of the pipe.

The second term in Eq. (11) ($\sigma I \eta n$) represents the "beam-induced desorption." This is outgassing caused by beam particles ionizing gas molecules in the vacuum pipe with these ions accelerated to the pipe wall and then knocking gas molecules off the wall. This term is directly proportional to the beam current I (protons/s), to the gas density n , to the proton-gas-ionization cross section σ , and to the desorption coefficient η , which gives the number of gas molecules produced per ion.

We first consider the steady-state case with $I = 0$:

$$C \frac{d^2 n}{dx^2} + g = 0 \text{ with } C \frac{\partial n}{\partial x} + S n = 0 \text{ at } x = \pm L . \quad (13)$$

For LAMPF II, we estimate $g = 1.26 \times 10^{+10}/\text{cm}\cdot\text{s}$

$$C_m = 9700 \pi \sqrt{\frac{T}{M}} \frac{(ab^2)}{8} = 3 \times 10^6 \text{ cm}^4/\text{s} \quad (14)$$

$$\text{with } (T = 300 \text{ K}, M \cong 30 \text{ (CO, N}_2\text{)}, a = 10 \text{ cm}, b = 5 \text{ cm}) . \quad (15)$$

Note that this conductance is a factor of 13.5 less than that of the PSR or ISR (where $a \cong b \cong 15\text{-cm diam}$). Vacuum would be substantially lower in those cases.

The solution of this equation is

$$h(x) = \frac{gL}{s} \left(1 + \frac{SL}{2C}\right) - \frac{gx^2}{2C} . \quad (16)$$

If we choose L at 2.5 m (as in PSR), which means 5 m between pumps, and require $\frac{SL}{2C} \lesssim 1$, we find $S \sim 24 \text{ l/s}$, and $n(\sigma) = 2.63 \times 10^8 \text{ cm}^{-3}$ or $P_{\text{max}} = 8.2 \times 10^{-9}T$, which is adequate.

Note that g corresponds to "degreased, mildly baked, exposed-to-air" beam pipe.² ISR beam pipe has $g \cong 100$ times smaller.¹ Also $g = FP$ is proportional to the outgassing rate of the material (F) times the beam pipe perimeter P . Combining with the previous result, we find ($SL = 2C$)

$$n(0) \propto L^2/a^2 , \quad (17)$$

indicating critical dependences on accelerator dimensions.

When the effects of beam-induced desorption (σ_{Inn}) and the time dependence ($A \frac{\partial n}{\partial t}$ where A is the beam cross section) are included, it is found that Eq. (18) has a solution of the following form:²

$$n(x,t) = \sum_{v=1}^{\infty} \cos \lambda_v x \left[\frac{C_v}{K_v} + \left(B_v - \frac{C_v}{K_v} \right) e^{-\frac{K_v t}{A}} \right] , \quad (18)$$

with λ_v found from the solutions of

$$\lambda_v \tan \lambda_v L = \frac{S}{C} , \quad (19)$$

$$C_v = \frac{2g \sin \lambda_v L}{\lambda_v \left[L + \frac{1}{2\lambda_v} \sin 2\lambda_v L \right]} , \quad (20)$$

$$K_v = C \lambda_v^2 - \sigma I \eta , \quad (21)$$

and

$$B_v = \int_{-L}^L \frac{n(x,0) \cos \lambda_v x}{L + \frac{1}{2\lambda_v} \sin 2\lambda_v L} dx . \quad (22)$$

The expansion in $\cos(\lambda_v x)$ with coefficients B_v expresses any initial condition $n(x,0)$ in terms of eigenfunctions.

Stability against beam-induced desorption requires $K_v > 0$ for all v ; that is,

$$C \lambda_v^2 > \sigma I \eta . \quad (23)$$

This is true if the lowest λ_v (λ_1) satisfies this relation. For our parameters ($SL/C = 2$, $L = 2.5$ m) $\lambda_1 = 0.00431 \text{ cm}^{-1}$. The parameter η is of order unity, therefore, we use a value $\eta \cong 0.25$. With $I_{\max} = 1 \text{ A} = 6.25 \times 10^{18} \text{ s}^{-1}$, $\sigma \sim 10^{-28} \text{ cm}^2$ and $C = 3 \times 10^6 \text{ cm}^4/\text{s}$. We find Eq. (24) becomes

$$55.7 \geq 6.25 (I\eta)_{\text{amperes}} , \quad (24)$$

which is easily satisfied at our parameters. We find that the vacuum should be reasonably secure from beam-induced adsorption instabilities.

An important vacuum requirement is that the vacuum remain adequate when one (or more) isolated pumps are nonfunctional, so that an isolated pump failure will not require an accelerator shut down. To estimate the effects of a pump failure, we simply double the pump spacing ($L \rightarrow 5 \text{ m}$) and find that the maximum pressure becomes

$$P_{\text{max}} \sim 2.5 \times 10^{-8} \text{ T} , \quad (25)$$

which is not too high.

Stability against ion desorption becomes less secure. With $L = 5 \text{ m}$ and S,C as above, we find $\lambda_1 = 0.0025 \text{ cm}^{-1}$ and

$$\eta I \lesssim 3 \text{ A} . \quad (26)$$

To improve stability, it is desirable to double the pumping speed (to 50 l/s) so that the stability limit becomes

$$\eta I \lesssim 10 \text{ A} . \quad (27)$$

To summarize the above discussions, we find that a vacuum system similar to the PSR system will be adequate for LAMPF II, provided the beam-pipe aperture is not significantly reduced.

REFERENCES

1. G. Guignard, CERN report 77-10 (1977).
2. G. Spalek, Los Alamos National Laboratory, Group AT-3, PSR Tech. Note 19 (1982).
3. K. H. Reich, K. Schindl, and H. Schönauer, "An Approach to the Design of Space-Charge Limited High Intensity Synchrotrons," (1983), Proc. XII Int. Conf. on High Energy Accelerators p. 438.

Pressure $\eta(x)$ at $t \rightarrow \infty$, $I \rightarrow 0$

Vacuum system outline.