MODELING PHOTO-DESORPTION IN HIGH CURRENT STORAGE RINGS

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ABSTRACT

We present a simple phenomenological model of photo-desorption that includes effects of dose dependence and diffuse photon reflection to compute the leveling of gas loads in beamlines of high current storage rings that typify heavy flavor factories. This model is also used to estimate chamber commissioning times.

I. INTRODUCTION

High luminosity flavor factories are characterized by high fluxes of synchrotron radiation that lead to thermal management difficulties. The associated photo-desorption from the vacuum chamber walls presents an additional design challenge, providing a vacuum system suitable for maintaining acceptable beam-gas lifetimes and low background levels of scattered radiation in the detector. Achieving acceptable operating pressures (1 – 10 nTorr) with practical pumping schemes requires the use of materials with low photo-desorption efficiency operating in a radiation environment beyond that of existing storage rings. Extrapolating the existing photo-desorption data base to the design requirements of high luminosity colliders requires a physical model of the differential cleaning in the vacuum chamber. We present a phenomenological model, including dose dependence of desorption and diffuse photon reflection, to compute the leveling of gas loads due to non-uniformities of radiation absorption in realistic beamlines. The model also allows one to estimate collider commissioning times.

II. WALL HEATING AND DYNAMIC GAS LOAD

To scale the vacuum system charcteristics as a function of collider performance one writes the thermal and photon loads on the chamber walls in terms of the luminosity, L;

$$L = \frac{N_- N_+ f_c}{4\pi \sigma_x \sigma_y} , \qquad (1)$$

where f_C is the collision frequency, N_- and N_+ are the charges in the electron and positron bunches, and σ_X and σ_Y are the horizontal and vertical beam sizes respectively. For beam-beam tune shifts, $\xi_x = \xi_y = \xi$, L scales with the beam current, I, and the β^*_y at the interaction point as

$$L = 2.7\times 10^{32}\left(\frac{\xi(E)}{0.05}\right)\left(\frac{I}{1\ A}\right)\times \left(\frac{4\ cm}{\beta^*_y}\right)\left(\frac{E}{1\ GeV}\right)(1+r)\ cm^{-2}\ s^{-1} , \qquad (2)$$

where r is the ratio of vertical to horizontal beam sizes.

The synchrotron radiation, P_{SR}, generated per beam is

$$P_{sr} = 88.5\ Watts\ E^4_{GeV}\ I_{mA}/\rho_m , \qquad (3)$$

where ρ_m is the bending radius in the ring. In terms of the dipole field strength, B_T, one can rewrite (3) as

$$P_{SR} = 26.5\ kW\ E^3_{GeV}\ I_A\ B_T. \qquad (4)$$

If the radiation is generated over $2\pi\rho_m$, the linear power density generated by each beam, P_L, is

$$P_L = 1.26\ kW/m\ E^2_{GeV}\ I_A\ B^2_T . \qquad (5)$$

Combining Eq. (1) and (5) yields the scaling law,

$$P_L = 12\frac{kW}{m}\left(\frac{L}{10^{34}}\right)\left(\frac{\beta^*_y}{1\ cm}\right)\left(\frac{0.05}{\xi}\right)\frac{B^2_T\ E_{GeV}}{1+r} . \qquad (6)$$

In high current electron storage rings the dynamic gas load due to photo-desorption is generally much larger than the static thermal outgassing of the chamber. The number of photons[1] incident on the chamber is

$$\dot{N}_\gamma = 8.08\times 10^{17}\ E_{GeV}\ I_{mA}\ photons/sec, \qquad (7)$$

A fraction, η_F, of the photons cause a gas molecule to be desorbed to produce a dynamic gas load (for an ideal gas) of

$$Q_{gas} = 2.4\times 10^{-2}\ E_{GeV}\ I_{mA}\eta_F\ \frac{Torr\cdot l}{s} . \qquad (8)$$

Combining Eq. (8) with Eq. (2) yields the scaling law for the pumping needed to maintain an operating pressure, P,

$$S = 6.7\times 10^5\ \frac{l}{sec}\left(\frac{5\ nTorr}{P}\right)\left(\frac{\eta_F}{1.5\times 10^{-5}}\right)\times \left(\frac{L}{10^{34}}\right)\left(\frac{\beta^*_y}{1\ cm}\right)\left(\frac{0.05}{\xi}\right)\frac{1}{1+r} \qquad (9)$$

The scaling laws show that large thermal and gas loads are the price of high luminosity; however, they are only estimates useful to scope the size of the gas and thermal management tasks. To locate and size the pumps one must account for localization of the gas load due the actual distribution of radiation deposited along the chamber walls. Naively, one might apply Eq. (7) and (8) directly using the radiation deposition profile with the adopted design value of η_F to compute the distributed gas load. Doing so, however, neglects the strong variation of η_F with dose.

III. PHENOMENOLOGICAL MODEL OF DESORPTION

The desorption coefficient is a property of the chamber which depends on several factors: 1) the chamber material, 2) the fabrication and preparation procedures, 3) the cumulative prior radiation dose, 4) the photon angle of incidence, 5) the photon energy. Given these complexities, rather than considering η_F to be a fundamental material property, one should regard it as an effective engineering characteristic that accounts for the differential illumination of the chamber walls both by direct (i.e., beam-produced) photons and by secondary, diffusely scattered and florescence photons. Using a single value of η_F in Eq. (8) predicts a gas load which is valid only to the extent that the desorption coefficient is constant along the beamline. Ignoring the non-uniformities can lead to a significant underestimate of the pumping required.

Recent experimental measurements[2, 3, 4] of η_F for samples of Al, stainless steel, and oxygen free Cu indicate minimum values of η_F ranging from $< 2 \times 10^{-6}$ for Cu and stainless steel to 2×10^{-5} for Al. From a typical set of data[3] in which effects of secondary photons are minimal one observes that for large exposures, η_F tends to follow a power law dependance on dose (photons/cm^2); i. e.,

$$\eta \propto (I t + t_o)^{-p} \qquad (10)$$

where t is the exposure time and $0.4 < p < 0.7$ (depending on material and preparation). Assuming that $p = 0.6$ for copper, one can compute a local value of $\eta_F(s)$ along the beamline. Then the gas load at a position, s, is

$$Q_{gas}(s) = \eta_F(s)\, \dot{N}_\gamma(s)\,. \qquad (11)$$

In the literature most workers present desorption data as a function of photons per cm or merely of Amp-hours. To compare data or to apply the data to a chamber conditioning scenario one must convert the dose to photons/cm^2.

As an example, consider the arcs of the 9 GeV ring of the asymmetric B factory based on PEP[5] (APIARY). The maximum allowed current is 3 A and the bending radius is 165 m. From Eq. (5) the maximum power is 102 W/cm with a distribution as illustrated by the dark curve in Fig. 1. By assuming that η_F assumes its design value where P_{SR} assumes its maximum value, one compute the relative gas load along a half-cell of the arc. This figure becomes a system specification for the vacuum engineer. The effect of the non-uniform exposure of the chamber is to level the gas load along the beamline and thus to require substantially more pumping capacity than would be needed if Q_{gas} were a constant multiple of the synchrotron power. For convenience this effect is termed "eta-leveling."

To extend the analysis one notes that although the synchrotron radiation fan cleans a thin band of height, H, around the mid-plane of the chamber, a large number of photons, from 20 - 50% of the number of primaries, are re-radiated or diffusely scattered. These secondary photons due to the effective albedo, R, illuminate rather uniformly the remainder of the chamber cross section of perimeter, P, as shown schematically in Fig. 2.

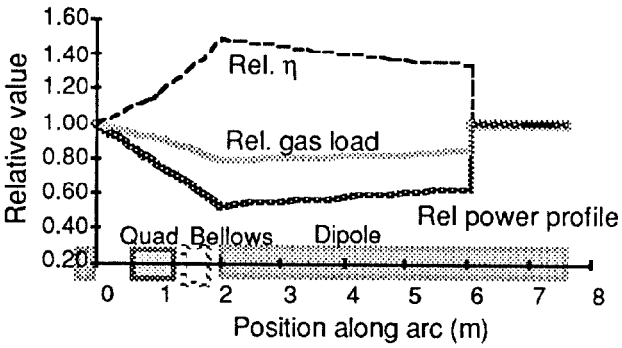

Figure 1. Relative distribution of synchrotron radiation, η, and gas load in arcs of 9 GeV APIARY ring.

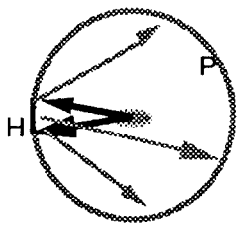

Figure 2. A cross section of the vacuum chamber in a bend

Though secondary photons have a much softer spectrum than the primaries, their photo-desorption efficiency is similar for energies exceeding a few tens of eV. Thus the remainder of the chamber perimeter is an important source of photo-desorbed gas, albeit one illuminated much more weakly, i. e., by a factor RH/P. With time, the effective desorption probability at a given location will vary as

$$\eta \propto (I t + t_o)^{-P} + R\,(I t \frac{R H}{P} + t_o)^{-P} \qquad (12)$$

As illustrated in Fig. 3, the effects of albedo and chamber geometry delay significantly the time at which the chamber attains a very low effective η_F. As the original power law behavior is eventually recovered for exposures >10 Amp-hr, the implications of the simple "eta-leveling" of the gas load remain accurate with respect to the pumping required with a well conditioned chamber.

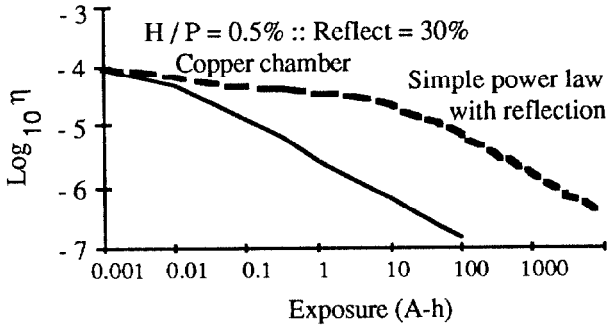

Figure 3. The effect of scattered photons on the dose dependence of the effective photo-desorption for a copper vacuum chamber.

The predictions of the phenomenological, eta-leveling model have been compared to the recent data of Ueda, et al.[4], which unlike exposures of Ref. 3 are dominated by secondary photons. Figure 4 compares data for lightly etched Cu, compared with a calculation with Eq. (12); the fit is very good for $0.5<p<0.6$. For $p = 0.62$ Fig. 5 shows the effect of chamber albedo on the effective η. The data are for an etched stainless steel chamber of which only 0.1% is directly illuminated. The authors estimate the albedo to be ≈50%. The model again displays good agreement. Note that if $R< 50\%$ for the storage ring, basing the vacuum design on the data of Ref. 4 represents a conservative choice.

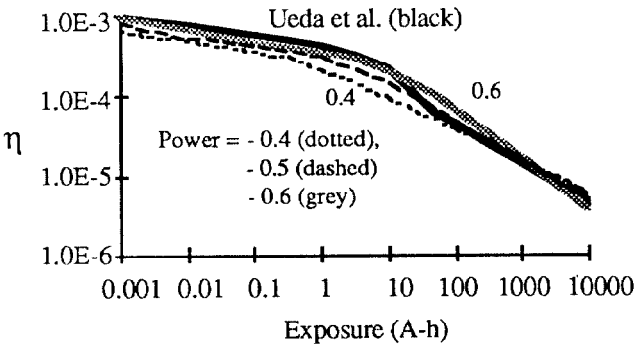

Figure 4. Comparison of the eta-leveling model with data from an etched copper test chamber

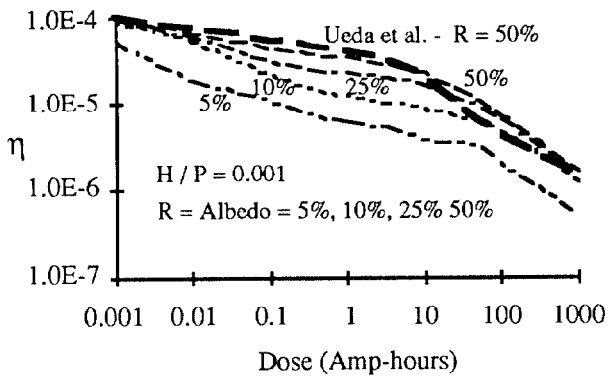

Figure 5. The dependence of η on chamber albedo

One use of the model is to specify a commissioning scenario for a high current storage ring. For a given the installed pumping the ring initially will be unable to maintain high current for a long lifetime. For the scattering lifetime to exceed ≈1 hour, one will be forced initially to store very low currents until η becomes sufficiently small that raising the current does not increase the operating pressure. Eventually, the chamber will be cleaned sufficiently by the radiation to allow operation at the full design current. A calculation for the high energy ring of APIARY, Fig. 6, shows that the design current (1.5 A) can be stored for >3 hours after ≈200 hours of operation.

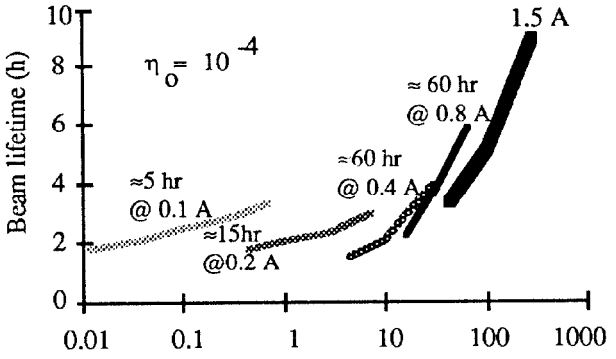

Figure 6. Commissioning scenario for the APIARY ring with an etched Cu vacuum chamber

In summary, a phenomenological model of the evolution of the effective photo-desorption coefficient, η_F, in high current storage rings is both a useful and necessary design tool. Without an adequate appreciation of the evolution of η_F, one is likely to underestimate the required pumping by as much as a factor of two and misjudge the commissioning time by an order of magnitude or more.

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IV. References

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[5] "An Asymmetric B Factory based on PEP - Conceptual Design Report", LBL PUB-5263, February, 1991.