VACUUM DESIGN FOR A SUPERCONDUCTING MINI-COLLIDER

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ABSTRACT
The phi factory (Superconducting Mini-Collider or SMC) proposed for construction at UCLA is a single storage ring with circulating currents of 2 A each of electrons and positrons. The small circumference exacerbates the difficulties of handling the gas load due to photo-desorption from the chamber walls. We analyze the vacuum system for the phi factory to specify design choices.

I. INTRODUCTION

To limit gas scattering that can limit collider performance one must maintain a low pressure in the vacuum chamber despite the copious synchrotron radiation generated by the high current beams. The heart of a sound vacuum system is a well designed vacuum chamber. The chamber must 1) withstand large thermal loads, 2) present a tolerable gas load to the pumps, 3) remain within the electromagnetic impedance budget. The designer of the vacuum system is faced with several options. The chamber may be of conventional "elliptical" shape or it may have an antechamber. The chamber material may be Al, stainless steel, or a Cu alloy as in HERA at DESY and as proposed for B factories by CERN, SLAC/LBL/LLNL (APIARY)[1] and Cornell (CESR-B). Each material allows alternate fabrication techniques.

II. THERMAL LOADS AND DESORPTION

Each beam generates a synchrotron radiation power, P_{sr},

$$P_{sr} = 88.5 \text{ Watts } E^4_{GeV} I_{mA} / \rho_m , \qquad (1)$$

where ρ_m is the bending radius in the ring. In terms of the dipole field strength, B_T, one can rewrite (1) as

$$P_{sr} = 26.5 \text{ kW } E^3_{GeV} I_A B_T. \qquad (2)$$

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

$$P_L = 1.26 \text{ kW/m } E^2_{GeV} I_A B^2_T . \qquad (3)$$

For SMC[2], E = 0.51, B_T = 4 T, and I = 2 A. The thermal load per beam is ≈ 10 kW/m. As both beams circulate in the same ring, the radiation fans overlap at the center of the bends yielding a local thermal load of ≈20 kW/m for an conventional elliptical vacuum chamber.

The power per unit area incident on the chamber wall depends on the height of the radiation fan at the wall. The height is a function of both the vertical angular spread, θ, of radiation from the beam electrons (or positrons) and on the distance, d, from the beam orbit to the wall. The angular spread from a electron of energy, E, is

$$\theta \approx \frac{m c^2}{E} = \gamma^{-1} . \qquad (4)$$

The half-height, h, of the radiation fan on the walls is related to the rms beam height, σ_y, the vertical emittance, ε_y, and the distance from the beam to the wall, d, by

$$h = \pm \left[\sigma_y^2 + d^2 \left(\left(\frac{\varepsilon}{\sigma}\right)_y^2 + \theta^2 \right) \right]^{1/2} . \qquad (5)$$

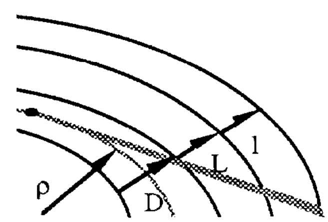

Figure 1. Geometry of chamber and radiation fan.

With the geometry of Fig. 1, which describes a beam chamber of width D, connected via a thin duct of length, L, to an antechamber of width, l, and using ρ = 0.42 m, D = 0.27 m, L = 0.2 m, and l = 0.14 m, we find d = 0.79 m. Thus, from Eq. (5) h = ±5 mm in the central dipole of the arcs and ± 2 mm elsewhere. These values are dominated by the heights of the electron and positron beams, which are 4.7 mm in the central dipole and 1.6 mm in the remainder of the collider. For the SMC, the P_{sr} ≈ 60 kW; thus, the maximum power density is 280 W/cm^2, one third the design value for the PEP ring at Stanford. In contrast the P_L for the 9 GeV ring of APIARY is ≈10 kW/m. For Cu alloys linear power densities ≈20 kW/m and areal densities ≈2 kW/cm^2 can be cooled with conventional techniques. Stainless steel, with its poor thermal conductivity, must be thin and backed by a OFHC Cu cooling bar. Forced water circulating in multiple channels keeps the vacuum chamber at a low enough temperature (<120° C) to cause negligible thermal desorption of gas into the system.

As the synchrotron radiation is not deposited uniformly, due to the alternation of bends and drifts in the ring, Eq. (6) represents the maximum P_L on the chamber. Applying an analytical formulation[3] for computing the distribution of radiation to the lattice of the SMC yields Fig. 2. The distribution is symmetric about the center of the detector (z = 0); the position of the detector and the superconducting dipoles are shown as boxes.

Following Gröbner, et al.[4], we compute gas load from the number of photons incident on the chamber:

$$\dot{N}_\gamma = 8.08 \times 10^{17} E_{GeV} I_{mA} \text{ photons / sec}, \qquad (6)$$

of which, a fraction, η_F, cause a molecule to be desorbed from the wall. For an ideal gas,

$$Q_{gas} = 2.4\mathrm{x}10^{-2} E_{GeV} I_{mA} \eta_F \frac{\mathrm{Torr} - \mathrm{l}}{\mathrm{s}} . \qquad (7)$$

The desorption coefficient decreases with the cumulative exposure of the material to synchrotron radiation. Several groups[5] have measured the photo-desorption from Al, Cu, and stainless steel, for conditions similar to the ones expected for the vacuum chamber of the SMC. As η_F depends only weakly on photon energy, our estimate of gas loading based on these data should be conservative.

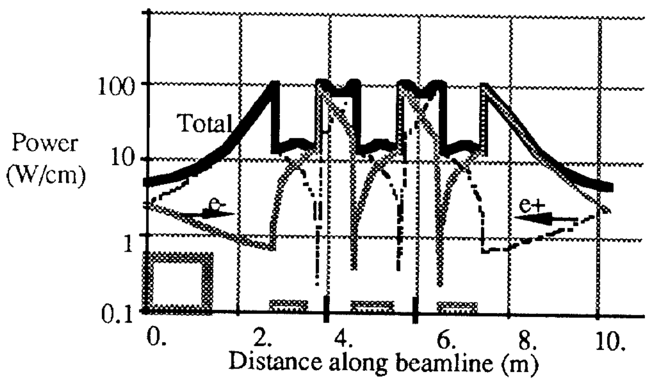

Figure 2. Distribution of radiation in the antechamber.

For the SMC, the dynamic gas load in an Al chamber with $\eta_F = 1.5 \times 10^{-5}$ is 7.2×10^{-4} Torr-l/s. To obtain a pressure of 5 nTorr requires 145,000 l/s or ≈20,000 l/s/m of pumping. These values are impractically high. In contrast, the use of an elliptical stainless steel chamber with $\eta_F = 2 \times 10^{-6}$ reduces the gas load to ≈ 10^{-4} Torr-l/s. The total required pumping would be ≈ 20,000 l/s or roughly 2,500 l/s/m of pumping distributed along the arcs. Therefore, we choose stainless steel as the chamber material. A more conservative alternative to stainless steel is copper which has excellent thermal conductivity and photo-desorption properties similar to stainless steel. Using Cu does require a considerably more difficult fabrication .

Even for an elliptical chamber of copper 2500 l/s/m is impractically large for either sputter ion pumps or non-evaporable getters (NEG). To lower the distributed pumping further we adopt an antechamber design in which the synchrotron radiation escapes from the beam chamber via a thin slot in the wall of the beam tube though a thin channel to an antechamber where it impinges on the wall. As the antechamber extends beyond the dipoles, large pumps can easily be located where the gas loads are produced. With the two chambered system of Fig. 3, the pumping speed can be reduced by a factor of ≈ 5.

The pressure in the inner chamber depends on the conductance[6], C, of the duct between two chambers. As the circumference is much larger than the duct height, we can approximate the slot as a thin, rectangular duct using the circumference as the width to obtain C = 900 l/s. To obtain pressure in a stainless steel outer chamber of 25 nTorr, the required pumping speed is 3.8×10^3 l/s. In that case the gas load in the inner chamber, where the beam is circulating is:

$$q = C\left(P_{out} - P_{in} \right) . \qquad (8)$$

The gas load in the beam tube is ≈1.8×10^{-5} Torr-l/s with an antechamber. The required pumping for an ultimate pressure of 5 nTorr in the beam tube is 3.6×10^3 l/s.

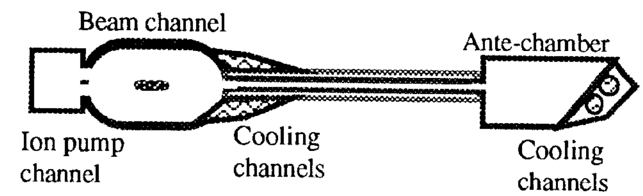

Figure 3. Ante-chamber cross section for the phi factory.

With a stainless steel chamber the combined pumping is 7,300 l/s or ≈600 l/s/m in the arcs, of which 400 l/s/m must be pumped from the beam tube. Although 400 l/s/m is well within the capability of NEG pumps, our estimate of the time between regeneration of the NEG is ≈100 hours, an unacceptably short interval. Even the difficulty of pumping the inner chamber may be surmounted. If we raise the pressure in the beam tube to 10 nTorr and lower the pressure in the outer chamber to 20 nTorr, the pumping requireed in the beam chamber falls to 90 l/sm well within the current practice in storage rings such as PEP which use distributed ion pumps requiring no regeneration.

The preceding discussion does not account for the variation of photo-desorption coefficient due to the non-uniformity of illumination of the walls of the chamber. The desorption efficiency decreases with long exposures, It, (in Amp-hours) approximately following $\eta_F \propto (It)^{-p}$ where $0.4 < p < 0.7$. Applying this variation increases the gas load ("eta leveling[7]") vis á vis a value simply proportional to P_L. The resulting gas load shown in Fig. 4.

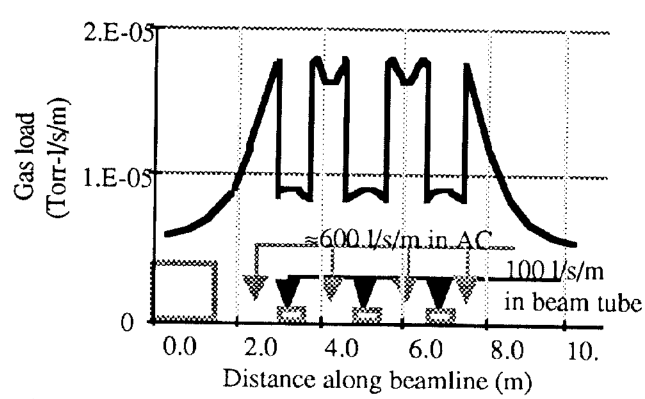

Figure 4. Distribution of gas load and pumping in SMC.

The antechamber is pumped with 600 l/s/m by either turbo-molecular, cryo-, or Ti sublimation pumps. The beam tube requires 100 l/s/m of pumping by a combination of turbo-molecular and distributed ion pumps. The pumping for the antechamber can be localized between the dipoles where the gas load is the highest. With our pumping scheme, the pressure distribution in the antechamber with 2 A per beam circulating is as shown in Fig. 5. The 100 l/s of distributed pumping in the beam tube reduces the pressure to less than 10 nTorr as required.

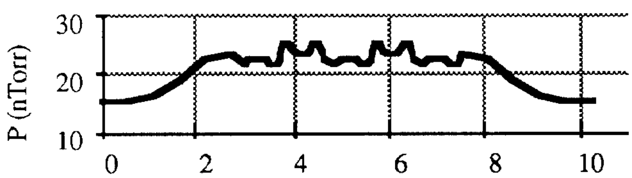

Figure 5. Pressure in the antechamber.

To assure an adequate quantum lifetime for the beams under all operating conditions, the vacuum chamber must be large enough to avoid depopulation of the wings of the beam. The physical aperture set equal to 12 times the beam size plus a closed orbit allowance and 5 mm for fabrication and alignment tolerances. For an elliptical chamber, one determines the horizontal and vertical radii from the maximum β_x and β_y, the maximum dispersion, ε_x and ε_y, and the closed orbit allowances. The most conservative assumption is to use the uncoupled ε_x and the fully coupled ε_y. Then, the radius of the beam stay clear is

$$\Sigma_i = 12\left[\varepsilon_i \beta_{i,\max} + \eta^2_{\max}\left(\frac{\Delta E}{E}\right)^2\right]^{0.5} + CO_i + 0.5 \text{ cm} \quad (9)$$

where i = x, y. Inserting the relevant lattice characteristics[2] of the phi factory (Table 1) into Eq. (12), we obtain chamber radii, Σ_x = 13.5 cm and Σ_y = 10.5 cm.

Table 1. Characteristics of phi factory optics

Uncoupled horizontal emittance	4 µm
Fully coupled vertical emittance	2 µm
Maximum horizontal beta	24 m
Maximum vertical beta	28 m
Maximum dispersion	0.8 m
Natural energy spread, ΔE/E	10^{-3}
Closed orbit, CO_x, CO_y	± 1, ± 0.5 cm

We have computed a conservative commissioning scenario for the SMC choosing an initial η_F of 10^{-3}, which is several times larger than achievable with good preparation techniques. Figure 6 shows that after ≈250 hours of operation the collider can be operated at the design current of 2 A with acceptable beam-gas scattering lifetime.

Engineers at LLNL have estimated the hardware cost of a stainless steel chamber with a copper cooling bar to be 175 K$ plus 120 K$ for the pumps, bellows and special hardware. Fabrication costs add an additional 130 K$. Use of copper for the entire design is likely to raise these costs by an additional 150K$. Hence, a stainless steel (copper) vacuum system for the SMC will cost ≈425 K$ (575 K$). Engineering, design and inspection adds an additional 650 K$ regardless of chamber material.

The SMC vacuum system, while more challenging than that of existing storage rings is within the bounds of sound engineering practices. The antechamber moves the gas load away from the beam thereby lowering the required distributed pumping. To minimize photo-desorption we have selected stainless steel backed by a Cu cooling bar for the chamber material. The x-ray opacity of stainless steel is sufficiently high over the entire range of photon energies that additional lead shielding is not needed to protect the superconducting magnets from the intense synchrotron radiation. Our design allows for chamber commissioning in ≈300 hours of ring operation. The cost per meter is relatively high, ≈50 K$/m, reflecting the considerable engineering effort required for this highly integrated and complex design.

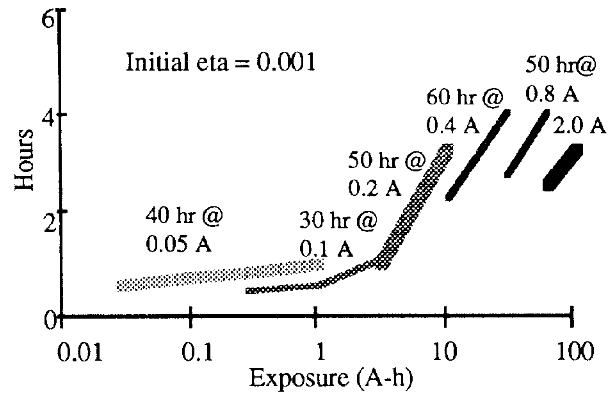

Figure 6. Beam lifetime during commisssioning.

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III. References

[1] *Investigation of an Asymmetric B Factory in the PEP Tunnel*, 1990. LBL PUB-5263, SLAC-359, CALT-68-1622

[2] William A. Barletta and Claudio Pellegrini, "Injection System for the UCLA Phi Factory" *Proceedings of the International Workshop on Phi factories and Related Physics Issues*, UCLA, April. 1990.

[3] A. Alexandrov, A. Hutton and, P. Legachev, *Synchrotron Radiation Power Calculations and Bending Radius Choice for the LER*, SLAC Internal Report ABC-13.

[4] O. Gröbner, et al., Vacuum 33, 397 (1983).

[5] See a) C. Foerster, H. Halama, C. Lanni, *J. Vac. Sci. Technol* A8 (3) 2856, 1990; b) A. Mathewson, et al., Comparison of Synchrotron Radiation Induced Gas Desorption from Al, Stainless Steel, and Cu Chambers, *Proceedings of the Symposium on Vacuum Systems for Synchrotron Radiation Sources*, Argonne National Laboratory, Nov., 1990 and c) Ueda, et al., Photo-desorption from Stainless Steel, Aluminum Alloy and Oxygen Free Copper Test Chambers, ibid.

[6] John F. O'Hanlon, *A User's Guide to Vacuum Technology*, John Wiley (1980).

[7] W. A. Barletta, Modeling Photo Desorption in High Current Storage Rings, This conference.