Abstract

ELECTRON STORAGE RING BEAM LIFETIME DEPENDENCE ON PRESSURE AND PUMPING

SPEED Henry J. Halama, Brookhaven National Laboratory, Upton, New York 11973. The beam loss in electron storage rings depends to a large extent on the interaction of the beam with heavier residual gas molecules such as CO, CO₂ and A due to Bremsstrahlung and Coulomb scattering. The gas density inside the vacuum chamber is determined by the surface condition of the vacuum chamber which is bombarded by photons (synchrotron radiation) generated by circulating electron beams and by the installed pumping. During the spring shutdown the X-ray ring vacuum system was updated and baked out. Residual gas spectra obtained were typical of a well baked out system i.e. hydrogen constituted ~ 95% of the gas and the average pressure was in the 10⁻¹⁰ Torr range. During initial operation the composition of desorbed gases was 43% H₂, 25% CO and 16% CO₂ and CH₄. After 3 months of beam conditioning desorption dropped by a factor of 5 and the CO, CO₂ and CH₄ peaks represented smaller percentage of total desorbed gas. Beam lifetime did not, however, show a corresponding increase. The pumping speed of distributed pumps dropped to zero at 1×10^{-9} Torr pressure but increased rapidly from 20L/s in low 10⁻⁹ as the pressure increased.

I. Introduction

The National Synchrotron Light Source NSLS contains two rings known as the UV and the X-ray rings which accelerate and store electron beams having an energy range from 700 MeV to 2.5 GeV. Thus they produce synchrotron radiation in a range¹ from 1 to 1200 Å. The most stringent requirement from the vacuum point of view is the large circulating average current of 1000 and 500 mA for the UV and the X-ray rings respectively. NSLS vacuum system has been described in detail in Ref. 1 and 2. Basically its vacuum chamber uses aluminum extrusions which provide room for distributed ion pump (DIP) in the

magnets. Straight sections of the beam tube are pumped by a combination of a 300 l/s ion pump and a titanium sublimator.

After the initial phase of commissioning during 1983 the following tasks were performed in March 1984.⁴

- a. The X-ray ring was thoroughly leak checked and all leaks were repaired. A few inaccessible leaks in welds, as well as a few small leaks which developed during the bake out were sprayed with Celvaseal manufactured by CVC. The ring was left leak free using detectors with sensitivity of 1×10^{-10} Torr ls^{-1} or better. The entire aluminum vacuum chamber was baked out above 100°C ($\sim 120^\circ\text{C}$ average), stainless tubes and ion pumps were baked to higher temperatures ($150 - 200^\circ\text{C}$). Hot nitrogen from LN_2 boil-off was bled through the ring during the warm up time (~ 4 hours) and the purging continued for ~ 1 hour after the equilibrium bake out temperature was reached. The purge was then stopped, the ring was evacuated and the bake out was continued for more than 30 hours.
- b. All filaments in the Ti sublimation cartridges were conditioned i.e. degassed at 50 A.
- c. All distributed and regular pumps were conditioned (turned on at high pressure and operated for ~ 1 minute. Pumps showing high leakage currents were "spark-knocked".
- d. 2 BA gauges and 2 mass spectrometers were calibrated and installed before the bake out.

After the bake out the average pressure in the X-ray ring was below 5×10^{-9} Torr (N_2 equivalent). Two days after sublimation the pressure dropped into the 10^{-10} Torr range and remained there. BA gauges mounted in the

vicinity of the ion pump read 1×10^{-10} Torr or less. Residual gas spectra confirmed that the bake out was a success, showing hydrogen content of 95%. The remaining 5% was due to CO, CO₂ and H₂O, in that order.

A typical spectrum taken with a RGA mounted in a magnet vacuum chamber is shown in Fig. 1. The large mass 19 peak is a F⁺ surface peak produced in the RGA ionizer.

II. Partial Pressure Analysis

In a leak-free, well baked out system the pressure depends on the outgassing rate which in turn is determined by the surface condition of the vacuum chamber and the installed pumping speed. Thus, it is rather easy to reach pressures in the 10^{-10} Torr range when no beam is present in the beam pipe (Fig. 1). When the beam is injected into the ring the synchrotron radiation desorbs gases from the walls and increases the gas load depending on the beam energy and the beam current (4-8).

The outgassing rate due to incident photons per m of chamber is given by

$$\frac{dO}{ds} = \frac{\dot{N} \eta_{ph} \eta_e}{2\pi R} f \left(\frac{1}{\sin \theta} \right) \quad (1)$$

where $\dot{N}$ = the number of photons per sec. per ampere of circulating current I
 $= 4.1 \times 10^{17} I \gamma$ (Ref. 4-7)

η_{ph} = photoelectron yield per photon

η_e = molecular yield per photoelectron

R = bending radius (m)

θ = the grazing angle of synchrotron radiation;⁷

γ = relativistic factor (beam energy relative to electron rest energy)

Since most desorption takes place in the curved magnet vacuum chambers and their adjacent front ends, 2 calibrated mass spectrometers were mounted in the X-ray ring; one behind the magnet X1BM1 and one in the front end next

to the magnet X2BM2. A typical residual gas spectrum is shown in Fig. 2 for a beam current of 52 mA at an energy of 1.7 GeV. It is seen that the content of CO and CO₂ has increased more than an order of magnitude as compared to no beam condition shown in Fig. 1.

In Fig. 3 we plot absolute pressures of several gas species for various beam energies and orbits obtained from the calibrated RGA at the X1BM1 location. The uncalibrated H₂ peak should be multiplied by 2.5 to arrive at its absolute value. Fig. 4 and Fig. 5 depict the partial pressure increase with increasing beam energy and current respectively.

The data shown in the last two figures suggest that the pressure increases faster with energy but more slowly with current than predicted by Eq. 7. The large scatter in the data taken in various runs prevents us from making a more qualitative comparison. Nevertheless the importance of a good surface condition, as well as of the pumping speed, becomes obvious if the design current of 500 mA at 2.5 GeV is to be attained. The final cleaning of the surface is, however, produced by synchrotron radiation itself and this effect is depicted in Fig. 6 as a function of time. During the initial stages of 1.7 GeV operation the desorbed gas content was 43% H₂, 25% CO - N₂, 16% CO₂ and 16% CH₄. It is seen from Fig. 6 that the desorption has decreased by more than a factor of 5 for a total dose of 7 ampere hours at 1.7 GeV and 12 A-hours at 750 MeV. The CO and CO₂ peaks also decreased compared to the H₂ peak. Additional 3 A-hours at 1.7 GeV showed only a small decrease in desorption possibly due to various problems in the machine and due to commissioning of Front Ends. From the RGA data we can conclude that the X-ray ring vacuum system is reasonably clean, leak-free and well baked out; similar to other electron storage rings.

III. Beam Lifetime

Among the mechanisms which determine the lifetime of the beam, Bremsstrahlung and single Coulomb scattering are the most important from the point of view of residual gas content. The time constant for Bremsstrahlung

$$\tau_B = \frac{X_0}{\rho c W} \text{ where}$$

X_0 = radiation length of residual gas,^{5,8} (g cm^{-2})

ρ = residual gas density (g cm^{-3}) = 5.48×10^{-8} MP

M = mass number in AMU

P = pressure in Torr

$$W = \frac{4}{3} \ln \frac{\gamma}{\Delta\gamma} - \frac{5}{6} = 5.3, \text{ for the X-ray ring}$$

$\frac{\gamma}{\Delta\gamma}$ or $\frac{1}{\epsilon_{RF}}$ = 100 and the beam lifetime due to Bremsstrahlung loss becomes

$$\tau_B = 3.2 \times 10^{-8} \frac{X_0}{\text{MP}} \text{ (hours)} \quad (2)$$

The lifetime τ_{SS} due to single scattering is given by

$$\tau_{SS} = \frac{1}{\sigma CN} \text{ seconds}$$

where N = residual gas density (molecules m^{-3})

$$= 3.2 \times 10^{22} P(\text{Torr})$$

C = velocity of light = $2.99 \times 10^8 \text{ ms}^{-1}$.

σ = scattering cross section (m^2)

$$= \frac{4\pi r^2 Z^2}{\gamma_{\text{max}}^2 \theta^2}$$

r = classical electron radius = $2.8 \times 10^{-15} \text{ m}$

Z = atomic number

γ = 3.3×10^3 for 1.7 GeV

$\theta_{\max}$ = maximum angle through which an electron may be scattered without being lost.

$$= \frac{d/2}{\sqrt{\langle \beta \rangle \beta_{\max}}} = 7 \times 10^{-4}$$

d = limiting aperture of the vacuum chamber assumed to be approximately 2 cm.

$$\langle \beta \rangle = 10 \text{ m}$$

$$\beta_{\max} = 20 \text{ m}$$

The lifetime for single scattering then becomes

$$\tau_{SS} = \frac{1.4 \times 10^{-6}}{Z^2 P} \text{ hours} \quad (3)$$

Using equations 2 and 3 beam lifetimes, τ_c , are calculated from partial pressures recorded on the calibrated RGA's and plotted in figures 3-6. They are compared in Table I with actual lifetimes, τ_m , obtained from beam current decay in the control room. The large discrepancy between τ_c and τ_m cannot be explained by the fact that the pressures used are being measured at one location only, since both calibrated RGA's are located where the desorption is maximum. BA gauges mounted at points other than in the magnets read considerably lower pressures. One exception to this is the R.F. cavity which under normal conditions operates in high 10^{-9} Torr, or low 10^{-8} Torr range⁸ changing the average ring pressure only slightly. Under certain conditions of local heating or X-ray desorption the pressure increases to the 10^{-7} Torr range and limits the beam lifetime which has been occasionally observed and correlated. In addition, large variations in τ_m are sometimes observed during the same series of runs without any apparent change in either the RGA reading or the general pressure readout.

A factor of 5 decrease in pressure due to beam conditioning (Fig. 6) is not matched by an equal increase in beam lifetime of only a factor of 2. We may therefore conclude that possible causes of the short beam lifetimes are likely to be related to other problems such as a smaller dynamic aperture than assumed in Eq. 3, ion trapping, equipment failures, various instabilities, R.F. problems, beam size, etc.

IV. Distributed Ion Pumps, DIP

Most desorption of surface gases by synchrotron radiation takes place in the curved magnets. In order to provide high pumping speed, where it is most needed, distributed pumps have been developed and their behavior at pressures from 10^{-8} to 10^{-4} Torr is reasonably well understood.⁹⁻¹² At low pressure their speed is dominated by:

1. the surface condition of the pump elements, i.e. the cleanliness and the amount of gases pumped previously.
2. discharge current density favors larger volume of individual Penning cells.

It is a well known fact that the pumping speed of ion pumps decreases drastically below 10^{-9} Torr range. In many cases the speed approaches zero or may even become negative i.e. the pumps release gases which were previously pumped. In systems where H_2 is the predominant gas, which is true for all UVH systems, the pumping speed is reduced due to poor sputtering of Titanium by H_2 ions.

Several attempts were made to measure dynamic pumping³ speed of DIP but due to inadequate instrumentation only the following observations could be made:

- a. N_2 equivalent pressure of $> 1 \times 10^{-9}$ Torr is required to ignite the pump at both 750 MeV and 2 GeV. The pumping speed below this pressure is zero.
- b. as the gas load increases due to desorption thus increasing the discharge current density, the pumping speed for CO increases from < 20 l/s at above 1×10^{-9} Torr to considerably higher values
- c. the pump appears to be clean i.e. no large gas loads are observed when the pump ignites.

Very low pumping speeds at low pressures were measured independently on a test stand,¹³ where a NSLS DIP was inserted into a magnet. At higher pressures from 10^{-5} to 10^{-8} Torr, the pumping speeds agreed reasonably well with the speeds of other ion pumps.

In order to confirm that the pumping speed of DIP is indeed very low, DIP's were switched off selectively while the circulating current was stored in the machine. Their effect on the beam lifetime was almost negligible. More details can be found in Ref. 3. Thus the only pumping available at 1×10^{-9} Torr in the magnets is due to the conductance from the adjacent titanium sublimators which amounts to $< 50 \text{ l s}^{-1}$, $< 40 \text{ l s}^{-1}$ and $< 150 \text{ l s}^{-1}$ for CO, CO₂ and H₂ respectively.

We conclude that below 3×10^{-9} Torr most of the pumping in the X-ray ring is done by Ti sublimation. The ion pumps remove only methane which is desorbed from the walls and traces of argon which would be emitted by the ion pumps if they were switched off. We are presently studying methods to increase DIP pumping speed in order to increase beam lifetime.

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Figure Captions

- Fig. 1. Residual gas spectrum with no beam.
- Fig. 2. Residual gas spectrum with 52 mA at 1.7 GeV.
- Fig. 3. X-ray ring partial pressure of main gas components at different energies.
- Fig. 4. Partial pressure increase, ΔP , of CO, CO₂ and CH₄ vs energy in the X-ray ring on July 18 (good port orbit).
- Fig. 5. X-ray ring beam current at 1.7 GeV vs partial pressure.
- Fig. 6. Beam conditioning of the X-ray ring; Partial pressure vs time.

TABLE I. Comparison of measured and calculated lifetimes

day	I	P(M=28)	Fig.	τ_c	τ_m	E	τ_c/τ_m	
	mA	10^{-9} Torr		min		GeV		
5/5	50	4	6	84	35	1.7	2.4	good port
6/28	51	1.2	5+6	264	51	1.7	5.17	good port
6/28	54	0.8	5	536	71	1.7	7.9	inj.
6/28	22	0.72	5	500	86	1.7	5.8	good port

Beam Current 52 mA
 Energy 1.7 GeV

Mass Spec Sensitivity

Fig 2

Fig 3

Fig 4

Fig 5

Fig 6

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