LIFETIME AND PERFORMANCE OF NSLS STORAGE RINGS*

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INTRODUCTION

The performance of synchrotron light sources is measured primarily in terms of beam lifetime, beam size, and the recovery of normal operation after a section of the machine has been brought to atmospheric pressure. The beam lifetime and the beam size depend on the following phenomena:

- a. Beam gas interaction which can be either elastic or inelastic scattering on residual gas nuclei or electrons. With the exception of low energy machines, this phenomenon represents the main limiting factor on lifetime.
- b. Beam interaction with trapped ions causing both beam loss and defocussing. Residual gas molecules are ionized both by circulating beam and synchrotron radiation. The cross sections for both processes are comparable. The effects of this phenomenon are most troublesome at low energies. The problem can be eliminated by switching to positron beams. Installing clearing electrodes has also been successful.
- c. Intrabeam scattering (Touschek effect) is caused by Coulomb scattering among electrons of the same bunch as they execute betatron oscillations. The Touschek effect is strongly dependent on energy and in general is a problem only in low energy machines.
- d. Various instabilities causing both slow and fast beam decay which have been observed in both NSLS rings. A special case due to dust particles that fall into the electron beam is commonly observed in early stages of conditioning. Coherent collective instabilities will not be discussed in this paper.

Optimum recovery of normal operation following installation of new components is achieved by:

- a. raising the temperature of the section to be vented and opened, in particular, the ion pumps;
- b. maintaining an elevated temperature during installation and pump-down;

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- c. using liquid nitrogen boil-off during bleed-up and purge while the section is open;
- d. preprocessing the components (glow discharge and bake out) before installation.

Since the NSLS is a dedicated facility, each ring vacuum system is tightly coupled to many beam lines which are isolated by front ends containing an all-metal valve, a fast valve, an instrument tee, and a pump (Fig. 1). Initial conditioning of the ring is carried out with all beam lines closed until acceptable lifetime is achieved. At this point, beam lines are opened when they satisfy the following criteria:

Total pressure $< 2 \times 10^{-9}$ Torr;
 H_2 content $> 60\%$

Masses above 28 AMU $< 10\%$

Hydrocarbons $< 1 \times 10^{-11}$ Torr.

Fig. 1 VUV Ring and its
 Beam Lines: FV - Fast
 Valve
 G/P - All metal valve
 I G - Ionization gauge

VUV RING

The vacuum system and the performance of the VUV ring prior to the August 1986 shutdown has been described in other publications¹⁻⁴. At that time, 2286 Ampere-hours of time-integrated beam current were accumulated. During the subsequent shutdown the following modifications were made:

1. Injection was modified to increase the aperture and pumping;
2. Four standard distributed ion pumps (DIP) were replaced with new plate type DIPs⁵;
3. The Transverse Optical Klystron system was installed;
4. All ion pump supplies were redesigned and the anode voltage increased to 5 kV;
5. Clearing electrodes were installed⁶.

Between the January 1987 start-up and March 1988, 2100 A-h were accumulated. Maximum beam current achieved was 1.3 A. This limit was imposed by machine components such as heating of ceramics and available rf power.

Continuous decrease in ring pressure due to synchrotron radiation cleaning of the chamber by photon stimulated desorption resulted in continuous improvement in lifetime. Lower pressure improves beam lifetime in two ways: less scattering from gas molecules, and less ion trapping which permits stacking more bunches in the machine. This in turn lowers electron density in the bunch and increases Touschek lifetime^{7,8}.

Typical performance versus beam current at 1700-2000 A-h is shown in Fig. 2. Switching to six bunches produces only a small improvement in lifetime and pressure.

In order to calculate beam lifetime, the partial pressures of all significant gas species (H_2 , H_2O , $CO-N_2$, and CO_2) averaged over the ring circumference (51 m) must be known. For this purpose, calibrated Bayard-Alpert gauges (BAG) and RGAs have been installed around the ring (Fig. 1). Relative pressures measured by RGAs are normalized to total pressure readings of BAGs.

The highest pressure, observed in bending magnets which comprise ~12 m of the circumference, varies linearly with beam current and reads ~11 nTorr at 1000 mA. In the rest of the ring (37 m), including the straight sections, the rf cavity, insertion devices, and injector, the pressure at 1000 mA is ~2.6 nTorr. This results in total average pressure of 4.6 nTorr with the following partial pressures:

H_2 (2)	=	3	nTorr
H_2O (18)	<	0.3	nTorr
$CO-N$ (28)	=	2.4	nTorr
CO_2 (44)	=	0.6	nTorr

Fig. 2 VUV Ring Measured Lifetime and Pressure VS. Beam Current

In the VUV ring, the pressure dependent lifetime is governed by three kinds of scatterings^{7,4}, i.e., Bremsstrahlung, τ_B , Coulomb scattering, τ_{CS} , and inelastic scattering on electrons, τ_{is} .

Assuming the following machine parameters: $\gamma = 1.46 \times 10^3$, $\epsilon_{rf} = 0.018$, $\langle \beta x \rangle = 5.7$ m, $\langle \beta v \rangle = 9$ m, $a_{\text{vert}} = 4$ cm, $\beta x_{\text{max}} = 13$ m, $\beta v_{\text{max}} = 15$ m, $a_{\text{hor}} = 8$ cm, and evaluating for each residual gas

$$\tau_B = \frac{3.7 \times 10^{-8} X_0}{MP} \approx 13.5 \text{ hours} \quad (1)$$

$$\tau_{cs} = \frac{3.3 \times 10^{-6}}{Z^2 P} \approx 9 \text{ hours} \quad (2)$$

$$\tau_{is} = \frac{2.6 \times 10^{-6}}{ZP} \approx 61 \text{ hours} \quad (3)$$

where X_0 = radiation length in g cm^{-2} , M = molecular weight in AMU, Z = atomic number, and P = pressure in Torr.

Summing up the above results, we obtain a total pressure dependent lifetime of 5 hours, which is to be compared with the measured lifetime of 92 minutes in Fig. 2. In an experiment with a very large vertical coupling a lifetime of ~240 minutes was measured. This shows an agreement with the calculated gas lifetime of ~20%.

There are three possible sources of error that could affect the calculated gas lifetime:

- a. inaccuracies in partial pressure measurements and their averaging;
- b. limiting vertical aperture smaller than 4 cm;
- c. presence of positive ions⁹ in the vacuum chamber not collected by BA gauges or RGAs.

However, inspection of Fig. 2 ($\sigma_v \approx 400 \mu\text{m}$) at emittance coupling of ~1%)¹⁰ strongly suggests that the lifetime is limited by pressure independent Touschek effect, which for a given machine is proportional to electron density within the bunch^{7,8} and depends on the rf acceptance. Using both the measured and the calculated lifetimes, Touschek lifetime

$$\tau_T \text{ at } 1 \text{ A} = 130 \text{ minutes}$$

$$\tau_T \text{ at } 500 \text{ mA} = 150 \text{ minutes}$$

$$\tau_T \text{ at } 250 \text{ mA} = 250 \text{ minutes}$$

The rather small increase in r_T with decreasing current is due to the bunch shortening¹⁰ which keeps the electron density in the bunch almost constant between 600 mA and 1.2 A. In a low emittance machine, the most effective way to increase Touschek lifetime is to lengthen the bunch with a harmonic cavity. A fourth harmonic cavity is at present being tested on the VUV ring with encouraging results^{11,12}.

After a long shutdown, both the beam current and the lifetime are generally limited by trapped ions in locally high pressure areas. This requires one or two bunch operations. Clearing electrodes installed in the ring⁶ were not effective in removing trapped ions, except in the early stages of operation when the pressure was high. In this case, about 10-20% improvement in lifetime and higher current threshold for the onset of beam defocussing were observed. Only the electrodes downstream of the dipoles drew high current, possibly due to high ionization cross section of low energy photons¹³ from dipole radiation. Our results differ markedly from those in Ref. 9, where a single clearing electrode yielded a 50% reduction in trapped CO^+ ions.

As the pressure in the machine improves due to synchrotron radiation cleaning, self-clearing permits more bunches stacked in the ring which in turn lowers electron density and increases Touschek lifetime. An increase of 5-10% in measured lifetime is observed when going from five to six bunch operation. In insertion devices such as wigglers and undulators which are good candidates for ion trapping due to their magnetic structure and copious photons, low pressure is essential and is achieved by installing two NEG strips, one on each side of the beam.

X-RAY RING

In February 1987, the X-ray ring was shut down for major modifications including:

1. Installation of four new insertion devices, three wigglers, and one undulator;
2. Installation of Laser-Electron-Gamma-ray-Spectroscopy Facility;
3. Six new dipole chambers¹⁴, including plate type DIPs, zero-degree ports, and NEG pumps;
4. Passive and active protection system;
5. Reworking of RF cavities;
6. Additional new front ends.

An updated schematic (Fig. 3) shows the new vacuum system and its components. Before the shutdown, 627 Ampere hours of time integrated beam had been accumulated. A maximum current 250 mA and a lifetime of 9 hours at 200 mA had been achieved¹⁴. Vacuum

performance of the X-ray ring during its entire operation is described in Ref. 3 and 15-17. The ring (170 m in circumference) is divided into sections according to the gas load. The pressures read on calibrated BA gauges and averaged over respective sections are tabulated in Table 1 for several currents

Fig. 3 X-Ray Ring and its Beam Lines

TABLE I

Amp- Hours	I mA	Straight Sections 1 = 114 m Torr	Magnets 44 m Torr	Cavities 12 m Torr	Average Pressure Torr
220	110	3×10^{-10}	1.7×10^{-9}	2.5×10^{-8}	2.4×10^{-9}
400	133	2×10^{-10}	1.5×10^{-9}	1.2×10^{-8}	1.5×10^{-9}
620	0	7×10^{-11}	3×10^{-10}	6×10^{-9}	4×10^{-10}
620	202	3×10^{-10}	2×10^{-9}	8×10^{-9}	1.3×10^{-9}

RGA scans normalized to BA gauge readings yielded the following partial pressures averaged over the ring circumference at 200 mA circulating current:

$H_2(2) = 1.3 \text{ nTorr}$
 $CO(28) = 0.7 \text{ nTorr}$
 $A(40) = 0.1 \text{ nTorr}$
 $CO_2(44) = 0.1 \text{ nTorr.}$

Fig. 4 X-Ray Ring Measured Lifetime and Pressure VS. i.e. Beam Current

The above partial pressures permit us to calculate the beam lifetime which can be compared with the measured value shown in Fig. 4. The circulating beam electrons interact both with the nuclei and the electrons of the residual gas atoms, but the total cross sections for nuclear interactions, i.e., Bremsstrahlung and Coulomb scattering, dominate the lifetime. Assuming rf acceptance of 1%, the Bremsstrahlung lifetime,

$$\tau_B = \frac{3.2 \times 10^{-8} X_0}{MP} = 36 \text{ hours} \quad (4)$$

Coulomb scattering lifetime⁷, τ_{cs} , for 2.53 GeV electrons assuming vertical aperture = 2 cm, $\langle \beta v \rangle = 10$ m, $\beta_{\text{max}} = 28$ m and $\tau = 4.95 \times 10^3$

$$\tau_{cs} = \frac{5.1 \times 10^{-6}}{Z^2 P} = 38 \text{ hours.} \quad (5)$$

For the scattering on electrons⁷, only the inelastic scattering is of any significance and the lifetime

$$\tau_{is} = \frac{2 \times 10^{-6}}{ZP} = 117 \text{ hours.} \quad (6)$$

From Eq. 3, 4, 6, we obtain the total calculated lifetime of 16 hours which is almost a factor of two larger than the measured value (Fig. 4).

As in the case of the UV ring, this discrepancy may be caused by similar errors, i.e.,

- a. inaccuracy in measured total and partial pressures;
- b. different limiting aperture than 2 cm used in (5)
- c. presence of positive ions⁹ trapped in the potential well of the beam.

Unlike the UV ring, both the lifetime and the pressure vary linearly with the beam current and the lifetime is therefore governed by residual gasses in the ring.

PRESENT STATUS

All the new vacuum chambers were baked out to -170°C for more than a week before they were installed in the ring. During the bake, they were dc glow discharged first in A 10% O₂ to remove surface contamination and then in N₂ to decrease photon stimulated

desorption (PDS) under beam operation¹⁸. Partial pressures were continuously monitored with an RGA to observe surface clean up. After the bake, the clean chambers were bled up to LN₂ boil off, transported to the X-ray ring, and installed. The entire ring was baked for approximately one week¹⁹. All pumps were regenerated and conditioned and all gauges and RGAs were degassed. At the end of March, the following pressures were recorded on calibrated gauges:

RF Cavities < 1×10^{-9} Torr

Straight Sections $\approx 2 \times 10^{-10}$ Torr

Magnets $\approx 4 \times 10^{-10}$ Torr

Ring commissioning started early in April. By April 18, the operating point was re-established and the orbit corrected. Injected current increased to 60 mA and 15 mA were accelerated to 2.5 GeV with a lifetime of 20 minutes. After one A-hour of conditioning at 2.5 GeV, lifetime of 1 hour at 60 mA was achieved. The entire ring was operating in the low 10^{-9} Torr range. During subsequent 2.5 GeV conditioning a steady improvement in lifetime was observed (with the usual beam drop-outs and bad lifetime modes. After 4 A hours 90 mA lifetime increased to 140 minutes.

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