SOME RESULTS OF THE ADVANCED PHOTON SOURCE BEAM LIFETIME STUDIES

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Abstract

Total beam lifetime consists of two components: the residual-gas-scattering lifetime and Touschek lifetime. The residual-gas lifetime is comprised of the elastic and inelastic scattering on electrons and elastic and inelastic scattering on nuclei. Touschek scattering involves scattering of particles within the bunch. One usually calculates only the elastic scattering on nuclei (single Coulomb scattering) and inelastic scattering on nuclei (bremsstrahlung) of the residual-gas-scattering lifetime component. Experience gained from computing the beam lifetime in the Advanced Photon Source (APS) storage ring shows that the electron scattering should not be neglected, particularly the inelastic contribution. Given the measured quantities from the APS storage ring, one can compare theoretical predictions with experimental results. Uncertainties in calculating the various contributions to lifetime will be discussed.

1 INTRODUCTION

Formulas exist [1, 2] to calculate both the residual-gas and Touschek components of the total beam lifetime. The inverse of the total beam lifetime is the sum of the inverses of the individual components.

The residual-gas component depends on the physical and energy apertures and on the properties of the gas mixture remaining in the storage ring, including the gas pressure. It is made up of elastic scattering on electrons, inelastic scattering on electrons, elastic scattering on nuclei (single Coulomb scattering) and inelastic scattering on nuclei (bremsstrahlung). The scattering on nuclei predominates, but scattering on electrons should not be neglected. Particularly elastic scattering on electrons contributes to the residual-gas lifetime. The Touschek component depends on the energy acceptance, momentum spread (which is related to bunch length), bunch current, Twiss parameters, dispersion, and coupling coefficient.

All such quantities are recorded in computer files for analysis. The experimentally observed lifetime is also recorded. This author has written a computer program that accepts this experimental data, computes the theoretically predicted lifetime, and compares this lifetime to the experimental value.

2 RESIDUAL-GAS LIFETIME COMPONENT

The presence of the residual gas, quantified by its pressure, may cause the positrons to either hit the wall or be ejected out of the bunch and get lost. The nature of gases present in the APS storage ring and their partial pressure was provided by John Noonan [3]:

Mass 2 (H_2)	48%
Mass 18 (H_2O)	24%
Mass 28 (CO/N_2)	23%
Mass 44 (CO_2) and remainder	5%

The gas density is related to pressure by:

$$P = \rho k T \tag{1}$$

where P is absolute pressure, ρ is gas density, $T = 300°K$ is absolute temperature and k is the Boltzmann constant (1.38×10^{-23} J/°K).

Given the pressure from data for a particular run, the above data can be used to calculate the loss rates of each gas in the mixture. The total residual-gas loss rate is the sum of loss rates of individual gases comprising the residual gas mixture. Total lifetime is the inverse of the total loss rate.

The formulas for each process of the residual-gas component are discussed below.

- Elastic scattering on nuclei leads to an angular kick for the betatron motion in the vertical direction:

$$R_{eln} = \frac{2\pi r_e^2 Z^2 c\rho}{\gamma^2}\left(\frac{\langle\beta_y\rangle\beta_y}{b^2}\right) \tag{2}$$

- Bremsstrahlung on nuclei leads to an energy loss for the circulating positrons:

$$R_{brn} = \frac{16 r_e^2 Z^2 c\rho}{411}\ln\frac{183}{Z^{1/3}}\left(\ln\frac{1}{\varepsilon_{acc}} - \frac{5}{8}\right) \tag{3}$$

- Elastic scattering on electrons results in transferring part of the positrons' incident energy to the electrons of the residual gas:

$$R_{ele} = \frac{2\pi r_e^2 Z c\rho}{\gamma}\frac{1}{\varepsilon_{acc}} \tag{4}$$

- Inelastic scattering on electrons leads to photon emission:

$$R_{ine} = \frac{16 r_e^2 Z c\rho}{411}\left(\ln\frac{2.5\gamma}{\varepsilon_{acc}} - 1.4\right)\left(\ln\frac{1}{\varepsilon_{acc}} - \frac{5}{8}\right) \tag{5}$$

where r_0 is the classical electron radius, c is the speed of light, Z and ρ are, respectively, the atomic number and the density of the residual gas, γ is the design energy divided by the rest energy of the positrons, $\langle\beta_y\rangle$ is the average vertical beta function around the ring, β_y is the vertical beta function at insertion, b is the vertical half-aperture, and ε_{acc} is the energy acceptance.

Solving Eq. (1) for ρ and substituting this into Eqs. (2) through (5) yields the loss rate of each process as a function of pressure. The loss rate is computed for each gas. The loss rates are added and the inverse is taken to compute the residual-gas component of the beam lifetime.

3 TOUSCHEK LIFETIME COMPONENT

The formulas for the Touschek component are

$$\frac{1}{\tau_T} = \frac{\sqrt{\pi} r_0^2 c N}{\gamma^2 (\delta p_x)^3 V} \int_{\varepsilon_{acc}}^{\infty} \frac{1}{u^2}\left(\frac{u}{\varepsilon_{acc}} - \frac{1}{2}\ln\left(\frac{u}{\varepsilon_{acc}}\right) - 1\right) exp(-u)\,du \quad (6)$$

$$\text{and } \varepsilon_{\text{acc}} = \left(\frac{\Delta p_{acc}}{\gamma \delta p_x}\right)^2, \quad (7)$$

where δp_x is related to the rms angular divergence, and V is the bunch volume [4]. The number of positrons in the bunch N is proportional to the bunch current I_b according to

$$I_b = eN\frac{c}{C}, \quad (8)$$

where e is the unit charge of a positron and C = 1104 m is the circumference of the APS storage ring.

In the lifetime calculation the bunch current is not measured directly, because no equipment is available at present. Rather, the beam current and number of filled buckets is available, so the bunch current is obtained by dividing the beam current by the number of buckets filled. This is only an approximation; a direct measurement of the bunch current is preferable.

The bunch length σ_l is a function of current I_b. From the available data, E. Crosbie [5] obtained the best fit. The empirical formula he provides is

$$\sigma_l = 7.344 + 1.388 I_b \quad (9)$$

with σ_l in mm and I_b in mA.

The coupling coefficient and energy acceptance are measured independently. Their values are 2.9% and 0.74%, respectively. The low value of the energy acceptance is attributed to high chromaticity, although the details are unknown.

4 ANALYSIS AND PRESENTATION OF RESULTS

In this report we ask: what values of the various quantities read from the input files will produce computed lifetime results that are comparable to the measured lifetime? First we take the measured quantities, including the measured lifetime, and write them to a file. The computer code uses this output file to compute the various lifetimes according to Eqs. (2) through (7) as well as the total beam lifetime. If the curves coincide (they never do), then the theoretical predictions are consistent with experimental results.

The input data are obtained from files that monitor many quantities of the storage ring. Each day is identified by its date, both Julian and conventional. SDDS tools developed by Michael Borland [6] are used to manipulate the data in those files. For this calculation all quantities (pressure, rf voltage, etc.) are expressed as a function of time of day. Therefore the time of day is the independent variable.

The runs of the storage ring are divided into two categories: machine studies and user runs. The machine studies analyze the overall performance of the storage ring and measure things such as energy acceptance, coupling coefficient, and other properties of the beam. The user runs set up experimental environments for the users. The purpose of the Advanced Photon Source is to provide high-energy X-rays for the users to use in their experiments. The user runs fulfill this purpose.

Beam lifetime studies are performed on selected user runs. The criterion is the continuity and smoothness of the measured beam lifetime curve over a prolonged period, say 7-10 hours. Before deciding whether or not a particular run is suitable for analysis, a plot of the measured lifetime as a function of time of day should be studied.

A standard run is one in which all quantities used in computing the beam lifetime come from the accelerator. Figure 1 displays computed total beam lifetime as well as the individual components, namely, the residual-gas component obtained from Eqs. (2) through (5) and the Touschek component obtained from Eqs. (6) and (7). The residual-gas component is further split into its major contributing processes, that is, the elastic scattering on nuclei obtained from Eq. (2) and bremsstrahlung obtained from Eq. (3). Figure 2 displays the total beam lifetime, contributions to the total beam lifetime from elastic scattering on nuclei and electrons obtained from Eqs. (2) and (4), contributions to the total beam lifetime from inelastic scattering on nuclei and electrons obtained from Eqs. (3) and (5), and Touschek lifetime. Figure 3 compares graphically the measured and computed total beam lifetime. In order to improve the readability of the graphical representations of the results, the lifetime axis is expressed in logarithmic scale.

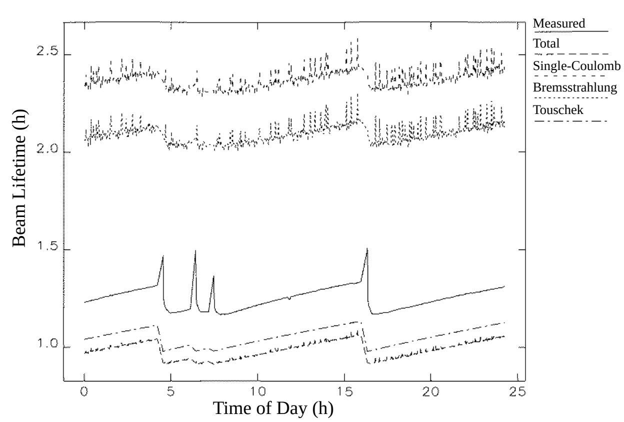

Figure 1: Measured and computed total lifetime, single-Coulomb lifetime, bremsstrahlung lifetime, and Touschek lifetime. The various lifetimes are in log scale.

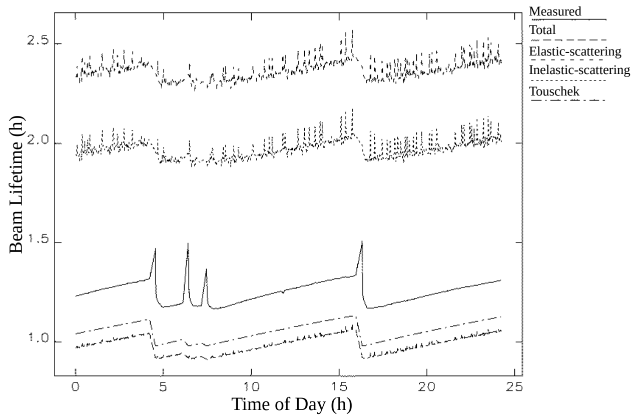

Figure 2: Measured and computed total lifetime, elastic-scattering lifetime, inelastic-scattering lifetime, and Touschek lifetime. The various lifetimes are in log scale.

Figures 1 through 3 represent the standard run. When changing some quantity to try to improve the beam lifetime, we direct our attention to Figure 3. Figure 4 shows the comparison of the computed and measured beam lifetimes if we increase the energy acceptance from 0.74% to 1%. The lifetime curves come closer together, improving consistency.

This investigation shows that better consistency can be achieved if the energy acceptance can be increased from 0.74% to 1%. The energy acceptance ought to be measured again to see if it can be made larger. If the comparison between the measured and computed lifetime is still poor, then other factors, such as the pressure, should be varied.

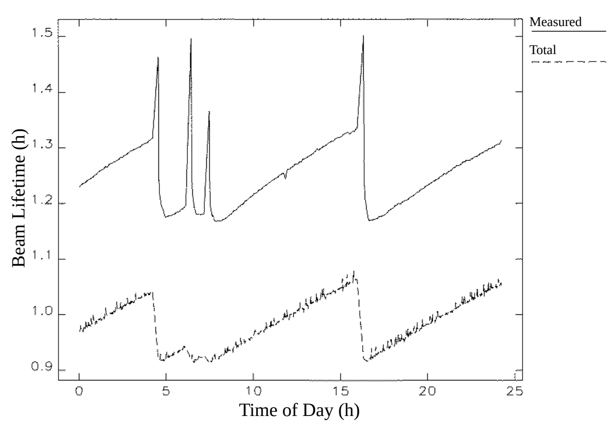

Figure 3: Measured and computed total lifetime. The various lifetimes are in log scale.

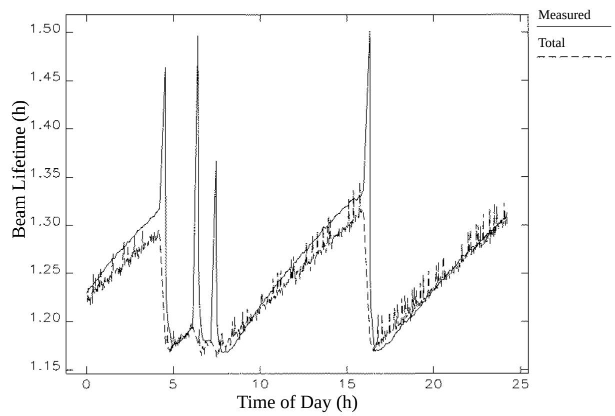

Figure 4: Measured and computed total lifetime with change in energy acceptance, as described in the text. The various lifetimes are in log scale

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6 REFERENCES

[1] H. Bruck, "Circular Particle Accelerators," Los Alamos National Laboratory, LA-TR-72-10, Rev.

[2] J. LeDuff, "Currents and Current Density Limitations in Existing Electron Storage Rings," *Nucl. Instr. and Meth*, A239, (1985).

[3] John Noonan, private communication.

[4] M. S. Zisman, S. Chattopadhya, J. J. Bisognano, "ZAP User's Manual," LBL--21270, December 1986.

[5] Edwin A. Crosbie, private communication.

[6] Michael Borland, "A Self-Describing File Protocol for Simulation Integration and Shared Postprocessors," Proc. of the 1995 Particle Accelerator Conference, pp. 2184-2186 (1996).