LIFETIME AND ACCEPTANCE OF THE SLS STORAGE RING

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Abstract

Beam lifetime at the storage ring of the Swiss Light Source (SLS) is limited by Touschek effect and elastic gas scattering. Both mechanism are affected by narrow gaps in the machine, elastic scattering directly by the vertical acceptance limitation, Touschek scattering via a possible restriction of lattice momentum acceptance due to coupling.

The particle loss mechanism was explored by evaluations of lifetime as function of scraper position, chromaticity and emittance coupling.

INTRODUCTION

Particle losses from a stored beam are partially due to single particle processes (e.g. scattering on residual gas atoms, losses at aperture limits) leading to an exponential decay of beam current with time, and partially due to two particle processes (e.g. intra beam scattering, beam-beam scattering) leading to a hyperbolic decay. In general it is a combination of both, like sketched in Fig. 1:

$$\dot{N} = -r_1 N - r_2 N^2 \;\Rightarrow\; N(t) = N_o \frac{e^{-\frac{t}{T_1}}}{1 + (1 - e^{-\frac{t}{T_1}})\frac{T_1}{T_2}}$$

Since lifetime is observed and measured for relatively short time intervals just the loss rates for $t \approx 0$ may be added. Total beam life time T thus is simply obtained as the inverse sum of single lifetimes T_i related to different processes : $1/T = \sum 1/T_i$. Attempts to express an hyperbolic decay by an exponential or vice versa (although frequently found in literature) do not make sense.

The SLS storage ring is a 12-TBA lattice of 288 m circumference, providing 5 nm·rad natural emittance at an energy of 2.4 GeV and a maximum beam current of 400 mA [1]. In this type of storage ring, the dominant processes of beam decay are elastic Coulomb scattering of beam electrons on residual gas nuclei, and Touschek scattering between electrons inside the bunch. A third, less important process is bremsstrahlung of electrons on residual gas nuclei. Quantum lifetime, i.e. direct losses from the tails of the Gaussian electron distribution are only observed in the final phase of a scraper experiment.

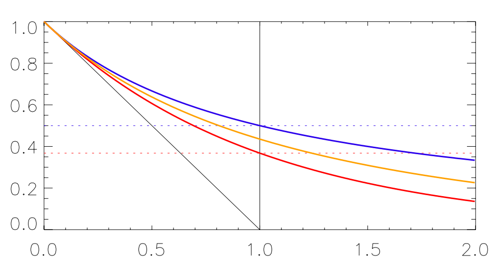

Figure 1: Exponential and hyperbolic beam decay: hyperbolic decay with half life time $T_2 = 1$ (upper curve, blue), exponential decay with $(1/e)$ life time $T_1 = 1$ (lower curve, red) and combined curve with $T_1 = T_2 = 2$ (middle curve, orange). Extrapolation of the slope at $t = 0$ gives for all curves $T = 1$ irrespective of the type of decay.

Elastic scattering lifetime is given by [2]

$$T_{\rm el} = \frac{\gamma^2}{K}\frac{A_z}{\langle\beta_z\rangle}\frac{\pi}{F(\rho)}\frac{\mathcal{T}}{r_p Z^2 N}\frac{1}{P}, \quad z = \begin{cases} x & \text{for } \rho > 1 \\ y & \text{for } \rho \le 1 \end{cases}$$

with $K = 2\pi r_e^2 c N_A / R = 1084$ msK/kg, and $\mathcal{T}$, r_p, Z, N gas temperature, relative partial pressure, atomic number and atoms/molecule, assuming that one species of gas dominates the lifetime. The function $F(\rho)$ takes into account a rectangular aperture providing transverse acceptances A_x and A_y:
$F = \pi + (1+\rho^2)\sin(2\arctan\rho) + (2\rho^2 - 2)\arctan\rho$
with $\rho = \sqrt{\frac{A_y}{A_x}\frac{\langle\beta_x\rangle}{\langle\beta_y\rangle}}$. $\rho \ll 1$ and $F \approx \pi$ for $A_y \ll A_x$. This approximation is fulfilled during normal operation of a light source due to the small vertical undulator gaps – but not when performing a horizontal scraper experiment.

Touschek lifetime is given as an integral of special functions of beam parameters and the local energy acceptance (EA) over the lattice circumference [3]. Before the onset of RF EA defined by the cavity voltage, dynamic aperture limitations may limit the local EA for particles scattered in dispersive region which have large betatron amplitudes. During damping of the synchrotron and horizontal betatron oscillations these particle may encounter coupling resonances inducing vertical betatron oscillations.

MEASUREMENTS

Elastic scattering lifetime measurements

Elastic scattering was explored by recording the lifetime while moving a vertical scraper into the beam as shown in Fig. 2. During the experiment the beam current and with it the pressure may change. Therefore the product of pressure P and lifetime T as a function of scraper position is evaluated. The theoretical shape including bremsstrahlung ($T_{\rm bs} = b/P$) and Touschek ($T_{\rm to}$) lifetime contributions is given by

$$T \cdot P = \left(\frac{1}{E\, y_{\rm scr}^2} + \frac{1}{b} + \frac{1}{T_{\rm to} P}\right)^{-1}.$$

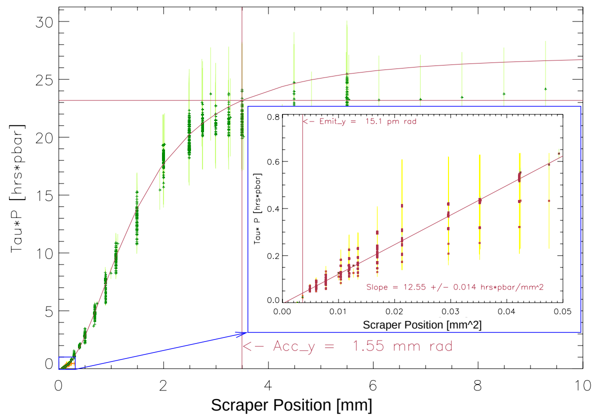

Figure 2: A measurement of beam life time as a function of vertical scraper position. The insert shows the region close to the origin magnified and scaled to the square of the scraper position. Green crosses show the measurement, the red lines indicate the fitted lifetime curve and estimates for vertical acceptance and emittance.

When moving in the scraper the life time does not change as long as the scraper remains outside the vertical acceptance, which thus is determined by the point where the scraper starts to take lifetime. The elastic scattering becomes dominant when the scraper approaches the beam, thus the straight line $TP = E\, y_{\rm scr}^2$ shown as insert in Fig. 2 allows to determine the slope $E = \frac{\gamma^2}{K}\frac{1}{\beta_{y\rm scr}\langle\beta_y\rangle}\frac{\mathcal{T}}{r_p Z^2 N} = 254\frac{\rm h\cdot pbar}{\rm mm^2}\cdot\frac{1}{r_p Z^2 N}$ for SLS, and with it the residual gas composition. Finally, when the scraper touches the beam, quantum lifetime takes over with a rapid beam decay, and provides a rough estimate of the vertical emittance.

The slopes E were found to be 12 h·pbar/mm^2 at 50 mA beam current and 28 h·pbar/mm^2 at 350 mA. Carbon monoxide is the relevant residual gas component, its relative partial pressure seems to decrease from 22% to 9% with increasing current, whereas the total average pressure increases from about 0.6 to 4 pbar.

The vertical acceptance, defined by the 2 m long extruded aluminum chamber of inner full height of 5 mm in one of the straights, was expected to be 3.0 mm·mrad. Measurements revealed a reduced value of less than 1 mm·mrad. By careful application of orbit bumps (complicated by immediate lifetime increase by any bump due to increased coupling from sextupoles!) the alignment status of the vacuum chamber could be measured, and subsequently a realignment was done raising the acceptance to 1.8 mm·mrad. More could not be achieved for yet unknown reasons. Later on, the vacuum chamber of a new wiggler [4] theoretically should have become the new acceptance limit of 2.5 mm·mrad, and measurement confirming the previous value of 1.8 mm·mrad proved the good alignment of the new chamber.

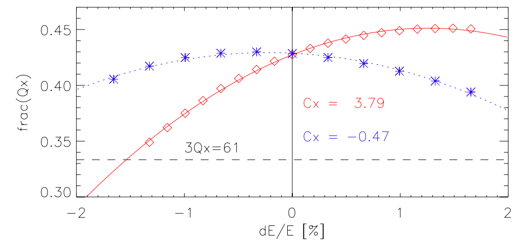

Figure 3: Measured horizontal fractional tune as a function of energy for “zero” chromaticity ($\xi_{x\rm set} = +0$ blue, dotted) and for increased chromaticity ($\xi_{x\rm set} = +5$ red, solid).

Touschek lifetime measurements

Previous measurements of Touschek lifetime as function of RF voltage and horizontal tune [5] indicated that the lattice EA rather than the RF EA determines lifetime, probably due to the $3Q_x = 61$ resonance encountered by off-energy particles at $\Delta E/E \approx -1.5\%$ (see Fig. 3) for large positive chromaticities as required for suppression of multi-bunch instabilities. Measurements of lifetime as function of a horizontal scraper located in a dispersive region were done for low and high chromaticity, the measurements are shown in Fig. 4 in comparison to a TRACY tracking simulation of Touschek lifetime including the scraper: at low chromaticity (Fig. 4, middle), the measurements follow exactly the theory, indicating that the RF EA of 3.1% from 4×460 keV RF voltage determines the lifetime. Under normal operating conditions (Fig. 4, top) measured values deviate from the theory already at $x_{\rm scr} \approx 9$ mm. This corresponds to the maximum excursion $x = (\sqrt{\beta_{x\rm scr}\mathcal{H}_{\rm max}} + \eta_{\rm scr})\cdot\Delta E/E$ of particles with $\Delta E/E \approx 1.5\%$ from the locations of maximum dispersion's emittance $\mathcal{H}_{\rm max}$ inside the TBA arcs, as to be expected from the $3Q_x = 61$ crossing in Fig.3.

When approaching the resonance in the measurement of Fig.3 a vertical beam blow-up was observed supporting the suspicion that the actual loss mechanism may involve coupling and losses at the narrow vertical apertures as predicted by early design studies [6] and observed at other places [7].

Recently an emittance monitor of sufficient resolution [8] came into operation and allowed to reduce the coupling $g = \varepsilon_y/\varepsilon_x$ from $g \approx 0.4\%$ to $g \approx 0.1\%$ by manually tuning six small skew quadrupoles for minimum beam height. When reducing the coupling we first saw a lifetime increase by about 20%, followed by a steep decrease: probably, first due to reduced coupling, vertical losses are avoided, then, with pure horizontal losses, Touschek lifetime follows the well known $T_{\rm to} \propto \sqrt{g}$ scaling. A third scraper measurement at low coupling and high chromaticity is shown in Fig. 4, bottom. Compared to large coupling (Fig. 4, top) the scraper onset is at larger values and the ratio of lifetime with scraper moved out to theoretical value improves from about 40% to 60%.

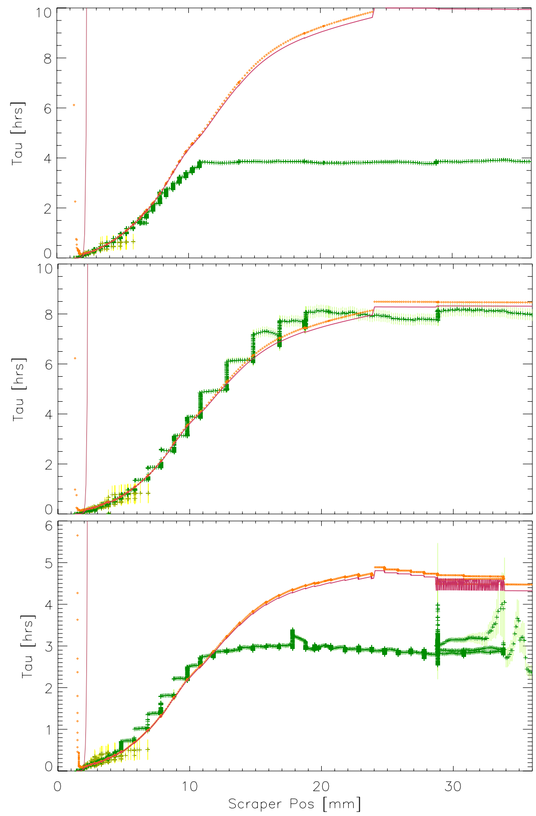

Figure 4: Lifetime as a function of horizontal dispersive scraper for different values of chromaticity ξ_x and emittance coupling g: top: $\xi_x = 3.8$, $g = 0.4\%$, middle: $\xi_x = 0.4$, $g = 0.4\%$, bottom: $\xi_x = 3.8$, $g = 0.16\%$. Green and yellow crosses are measured values, orange dots calculated Touschek lifetime based on tracking data, red curve total lifetime (incl. hor. and vert. elastic scattering and bremsstrahlung), left red line is quantum lifetime.

To explore this further, double measurements of lifetime as a function of *vertical* scraper were done: a first run with 50 mA in 390 buckets to have elastic scattering dominated lifetime and to extract the slope E was followed by a second run with 50 mA in 50 buckets to have a Touschek dominated lifetime. Fig. 5 shows the pure Touschek lifetime data obtained from subtracting the first data from the second data for the same three cases like shown in Fig. 4: Obviously, for high chromaticity and coupling, the Touschek lifetime is affected by the vertical scraper (Fig. 5, top), but this is not the case for low chromaticity (Fig. 5, middle). With reduced coupling (Fig. 5 bottom, unfortunately disturbed by noise), the situation improves compared to high coupling.

OUTLOOK

Vertical acceptance is well understood. Energy acceptance and Touschek lifetime are subject of ongoing studies. Decreased coupling reduces vertical losses and improves the Touschek lifetime. However direct horizontal losses still seem to occur due to crossing of a third integer resonance. Suppression of this (non-systematic) resonance by improved machine symmetry or by a new sextupole pattern is planned. Studies on horizontal acceptance using scrapers and pingers have just been started.

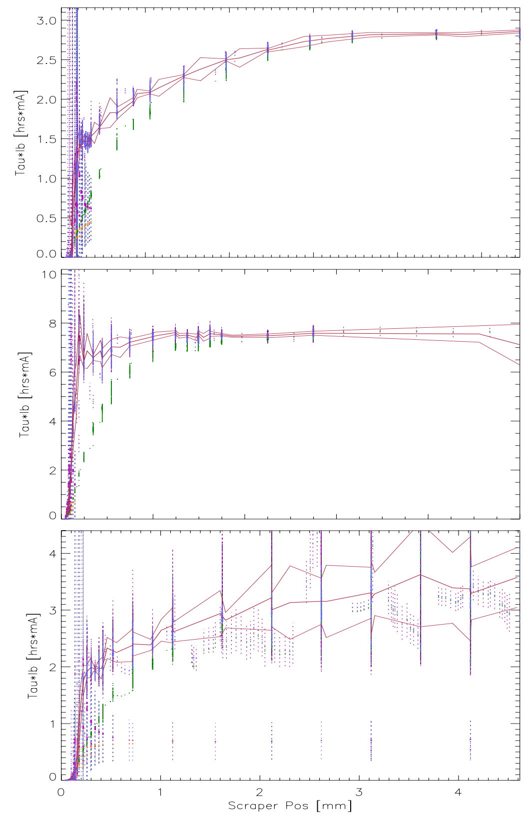

Figure 5: Touschek lifetime normalized to current as a function of vertical scraper for the three cases from Fig. 4. Green dots are measured values, blue dots connected by the purple center line are pure Touschek lifetime values after subtraction of elastic scattering lifetime. Purple side lines give an error estimate.

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