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Beam Lifetime in the SLS Storage Ring

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Abstract

Three shifts in Nov. and Dec. 2001 were spent on beam lifetime measurements. Elastic gas scattering was measured by moving scrapers into the beam. Touschek lifetime was measured as function of single bunch current, RF voltage and tune. Analysis of Touschek lifetime provided information on the energy acceptance and its limitation due to a sextupolar resonance, and on the value of emittance coupling. Indications for turbulent bunch lengthening were found and evaluated to estimate the longitudinal broad band impedance.

Introduction

Dominant processes for particle losses in a machine like the SLS storage ring are elastic scattering on residual gas nuclei leading to transverse deflection and subsequent loss at transverse aperture limitations and Touschek scattering between electrons in a bunch leading to energy changes exceeding the machine's energy acceptance. A third, less important but non negligible process is bremsstrahlung on residual gas nuclei, also leading to energy losses exceeding the acceptance. Other processes as scattering on residual gas electrons and losses of the core beam's gaussian tails (quantum lifetime) are negligible for SLS.

Elastic scattering and bremstrahlung on nuclei are single particle processes thus following an exponential law with τ the decay to $1/e$, whereas Touschek scattering is a two particle process following an hyperbolic law with $T_{1/2}$ the decay to 1/2.

Elastic scattering is well studied by moving a scraper into the beam, since it is sensitive on the transverse acceptance. Touschek scattering depends on bunch density and energy acceptance and thus can be studied by variation of single bunch current and RF voltage. Bremsstrahlung depends only weakly on the energy acceptance and cannot be isolated for study. It is just the residue left after careful measurement of the other processes.

Elastic scattering lifetime measurements are required to prove the average pressure calibration and to subtract the contribution from the total lifetime for further studies. Since Touschek lifetime depends on the bunch density, measurements provide valuable information on bunch length as function of current and of vertical emittance, which are quantities difficult to predict during machine design and to observe by other means.

SLS Storage Ring Parameters

The table below summarizes the parameters of the SLS storage ring relevant for this study. The magnet optics corrsponds to the present (Dec.2001) standard mode of operation D2Rc with measured and corrected betafunctions. The parameters listed below were set, resp. assumed through the measurements and used for the calculation if not mentioned different in the text below.

Parameter	Symbol	Value	Unit
beam energy / normalized to rest mass	E / γ	2.4 / 4697	GeV / 1
circumference	C	288	m
linear momentum compaction factor	α	$6.5 \cdot 10^{-4}$	
natural Emittance	ε_{xo}	5.03	nm·rad
energy loss per turn (no IDs, no wakefields)	U_o	512	keV
relative energy spread (rms)	σ_e	$8.6 \cdot 10^{-4}$	
bunch length (rms) for $V_{\text{rf}} = 2.0$ MV	σ_{so}	4.0	mm
horizontal / vertical tune	Q_x / Q_y	20.38 / 8.16	
horizontal / vertical chromaticity (measured)	ξ_x / ξ_y	1.6 / 0.5	
horizontal / vertical average betafunctions	$\langle\beta_x\rangle$ / $\langle\beta_y\rangle$	7.64 / 8.83	m
vertical betafunction at scraper location	$\beta_y\vert_{\text{scraper}}$	7.6 (± 0.25)	m
vertical acceptance limit (9L: ±8 mm, $\beta_y\vert_{\text{edge}} = 11.5$ m)	A_y	5.5	mm·mrad
residual gas (CO): atomic number; atoms per molecule	Z;N	7;2	
residual gas (CO) partial fraction	r_p	$\approx$ 0.2	
residual gas temperature	T	300	K
Useful constants			
classical electron radius	r_e	$2.818 \cdot 10^{-15}$	m
speed of light	c	$3 \cdot 10^8$	m/s
universal gas constant	R	8.314	J/(K·mol)
Avogadro's constant	N_A	$6.0223 \cdot 10^{23}$	1/mol

Theoretical Foundations

Elastic Scattering

The formula as used in ZAP[1], expressed in SI units, is given by

$$\frac{1}{\tau_{\rm el}[\rm s]} = \frac{2\pi r_e^2 c N_A}{R\gamma^2} \frac{\langle\beta_y\rangle}{A_y[\rm m{\cdot}rad]} \frac{r_p Z^2 N}{T} P[\rm Pa] \tag{1}$$

if there is only one dominant gas species. We also assumed already that the elastic scattering is fully determined by vertical acceptance limitations, which is the case for SLS with narrow gap insertion devices. The vertical acceptance A_y is given in a scraper experiment by

$$A_y = \left.\frac{\Delta y^2}{\beta_y}\right|_{\rm scraper}$$

where Δy is the distance of the scraper blade from the position for total beam loss.

Introducing the constants and the SLS specific parameters, the elastic scattering lifetime in practical units can be written as

$$\tau_{\rm el}[\rm h] = 1920 \frac{A_y\ [\rm mm{\cdot}mrad]}{r_p Z^2 N P[\rm pbar]} \tag{2}$$

If we assume a 20%-fraction of carbon monoxide (Z=7,N=2) and introduce the local betafunction at the scraper we finally arrive at

$$\tau_{\rm el}[\rm h] = 12.9 \frac{(\Delta y[\rm mm])^2}{P[\rm pbar]} \tag{3}$$

Bremsstrahlung

The ZAP-formula in SI-units is given by

$$\frac{1}{\tau_{\rm bs}[\rm s]} = \frac{4 r_e^2 c N_A}{137 R} L(\delta_{\rm acc}) \ln \frac{183}{\sqrt[3]{Z}} \frac{r_p Z^2 N}{T} P[\rm Pa] \quad \text{with} \quad L = \frac{4}{3}\left(\ln\frac{1}{\delta_{\rm acc}} - \frac{5}{8}\right) \tag{4}$$

a function depending weakly on the energy acceptance $\delta_{\rm acc}$ of the machine:

$\delta_{\rm acc}$	2	3	4	5	%
$L(\delta_{\rm acc})$	4.37	3.84	3.45	3.16	

Assuming $\delta_{\rm acc} = 3$ % and again 20 % of CO as relevant gas, we get

$$\tau_{\rm bs}[\rm h] = 480 \frac{1}{P[\rm pbar]} \tag{5}$$

Touschek Scattering

Touschek lifetime is not given by a simple formula but has to be calculated as an integral over the ring circumference involving local beam parameters and local energy acceptances, which can be either determined by the RF voltage or by the lattice off-energy acceptance [2]. At least Touschek lifetime scales with the single bunch current and with the square root of the emittance ratio g (as long as the beam is flat, i.e. $g \ll 1$).

Quantitative results require tracking studies. A quick tracking was done for SLS/D2R using the OPA-code [4] including nonlinear transverse motion, but not including nonlinear longitudinal motions, true synchrotron oscillations, lattice errors and halo coupling. The results of Touschek half life times for different RF-voltage values are given below. Tracking assumed 1 nC of bunch charge (corresponding to 1.04 mA) and 0.2 % emittance ratio:

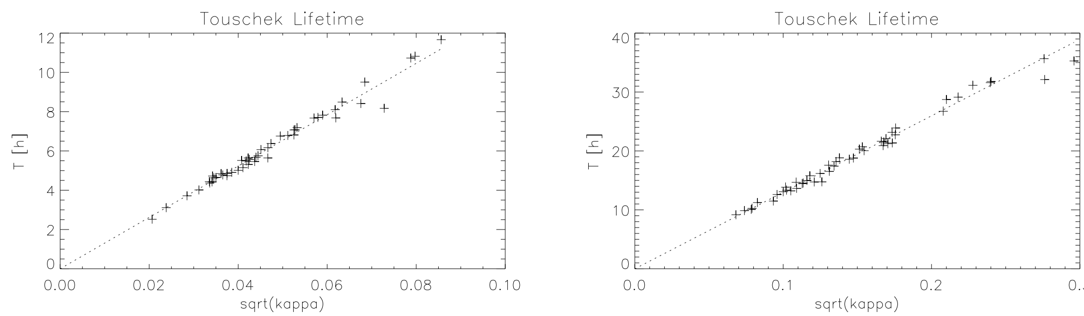

Figure 1: Simulation: Touschek lifetime vs. square root of emittance ratio g (here called `kappa`)

left: Displacement / roll errors of 50 μm / 100 μrad for elements (magnets and BPMs) relative to the girder, 300 μm / 25 μrad for girders absolute and 100 μm / 0 for girder joints.
Result: $\langle T_{1/2}/\sqrt{g}\rangle$=131 h, $\langle g\rangle$=0.25 %

right: same calculation but roll errors 10 times larger (1 mrad for elements, 0.25 mrad for girders) to force higher emittance ratio.
Result: $\langle T_{1/2}/\sqrt{g}\rangle$=130 h, $\langle g\rangle$=2.54 %

Lattice D2R, $V_{\rm rf} = 2.0$ MV, 1 nCb bunch charge. 50 seeds with gaussian error distribution cut at 2σ, tracking 234 turns (1.5 synchrotron oscillations)

RF voltage	$V_{\rm rf}$	1.0	1.5	2.0	2.5	3.0	MV
RF energy acceptance	$\delta^{\rm rf}_{\rm acc}$	1.65	2.55	3.24	3.81	4.31	%
Touschek half life time	$T_{1/2}$	1.39	3.67	6.29	9.01	10.9	h

More precise TRACY [5] calculations including all effects neglected in OPA and assuming 50 seeds of reasonable random errors are shown in figure 1 (left) gave an average lifetime normalized to emittance ratio of $\langle T_{1/2}/\sqrt{g}\rangle$=131 h. The lifetime value comparing to OPA's 6.29 h in the above table's center column thus would slightly reduce by 7 % to 5.85 h. Assuming an exponential decay for the sake of comparison and normalizing to emittance ratio and beam current we thus may write

$$\tau_{\rm ts}\ [\mathrm{h}] \ = 19.6\ \frac{\sqrt{g[\%]}}{I_{\rm b}[\mathrm{mA}]} \quad \text{for } V_{\rm rf} = 2.0 \text{ MV} \tag{6}$$

Total Lifetime

The three loss rates simply add up, i.e. the lifetimes add up inversely:

$$\frac{1}{\tau} = \frac{1}{\tau_{\rm el}} + \frac{1}{\tau_{\rm bs}} + \frac{1}{\tau_{\rm ts}}$$

Bunch Lengthening

Touschek lifetime scales linearly with the bunch length. (However, if the bunch lenghtening is large and correlated with energy spread widening, corresponding increase of transverse beam sizes in dispersive regions will modify the scaling). Observation of lifetime for high single bunch currents thus may provide information on bunch lengthening thresholds and the impedance involved.

According to theory [1] the bunch lengthening factor $x := \sigma_s/\sigma_{so}$ as function of single bunch current I_b is given beyond the threshold for onset of turbulent bunch lengthening (TBL) (also referred to as microwave instability) by

$$x = \left(K \left| \frac{Z_\parallel}{n} \right|_o^{\rm bb} I_b \right)^A \quad \text{for} \quad I_b > I_b^{\rm th} \tag{7}$$

with the TBL exponent $A = 1/3$ usually, the TBL threshold I_b^{th} given for $x = 1$ from the above equation, and

$$K = \frac{C}{(2\pi)^{3/2}\alpha(E/e)\sigma_e^2\sigma_s} = 3960\ \mathrm{V}^{-1} \quad \text{for SLS at } V_{\mathrm{rf}}\text{=2 MV.} \tag{8}$$

The impedance involved in TBL is the total longitudinal impedance of the ring approximated by a broad band resonator centered at the beam pipe cut-off frequency.

For convenience of evaluation, the TBL equation can be written as

$$\ln x = \underbrace{A \ln \left(K \left| \frac{Z_\parallel}{n} \right|_o^{\mathrm{bb}} \right)}_{B} + A \ln I_b \tag{9}$$

with A and B slope and intercept of a straight line.

Measurements

Data acquisition and reduction

Three shifts on Nov.27$^{\mathrm{th}}$, Dec.3$^{\mathrm{rd}}$ and Dec.10$^{\mathrm{th}}$ 2001 were spent on lifetime studies with the series of measurements listed below:

No.	Measured vs. Varied (Comment)	Buckets	$\Delta\xi_x$/ $\Delta\xi_y$
1.1	lifetime and pressure vs. top scraper (not used)	390	1.3/4.0
1.2	lifetime and pressure vs. top scraper	240	1.3/4.0
1.3	lifetime and pressure vs. current	240	1.3/4.0
1.4	lifetime and beam radii (pinhole camera) vs. current	120	1.3/4.0
2.1	lifetime and pressure vs. top and bottom scraper	390	2.0/4.5
2.2	lifetime and pressure vs. current	30	2.0/4.5
2.3a	lifetime vs. RF voltage	30	0.0/1.0
2.3b	lifetime vs. RF voltage	30	2.0/4.5
3.1	lifetime and pressure vs. top scraper	380	2.0/4.5
3.2	lifetime vs. RF voltage	30	1.0/1.0
3.3	lifetime and pressure vs. current	30	1.0/1.0
3.4	lifetime vs. tunes	30	1.0/1.0

The injector operated in single pulse mode in order to inject a clean, rectangular filling pattern, with the above given number from 480 available buckets filled. Different chromaticity shifts to be added to the nominal chromaticities of +1/+1 (design). resp. +1.6/+0.5 (measured) were used.

If not otherwise mentioned, following conditions were set: The machine operated in D2Rc optics with nominal tunes of 20.38 and 8.16. All four cavities were operating at 565 kV each, appeerently well balanced with low reflected power. All insertion devices were inactive, except wiggler W61 was closed during series 1.2, however it was felt, that this had no effect.

Series 2.3a and b were measured together, alternating the chromaticity between the two settings.

The application for lifetime display obtains the values from a linear fit to the parametric current transformer readings delivered at a rate of 0.5 Hz[8]. In order to obtain a stable lifetime value, the sufficient number of points had to be as large as 45, thus making the measurements rather lengthy. For lifetimes shorter than approx. 1 h, also the inverse of the current rate of change could be used, which is much faster. A strip chart application drawing lifetime was running in order to visualize the “settling” of the lifetime to a changed value.

Errors on the lifetime values were estimated by observing the fluctuations and ranged between 1 and 10 %. In series 3.1-3.4 no individual errors were recorded but errors of 5 % or at least 1 minute were assumed based on previous experience. Compared to this, most other quantities like pressure and current were considered as error-free.

Several linear fits were done including checks of χ^2/ν (with $\nu = N - 2$ the number of degrees of freedom, N the number of measurements, $\chi^2/\nu < 1$ for a meaningful fit), calculation of slope and intercept errors from the covariance matrix and subsequent error propagation for derived quantities.

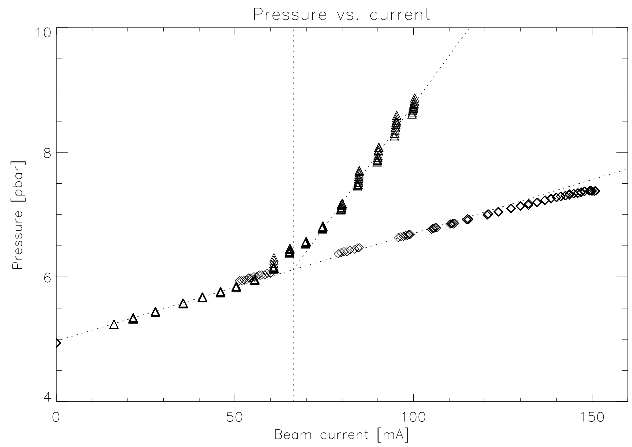

Figure 2: Measured average pressure as a function of total beam current: $\diamond$ series 3.1, $\triangle$ series 3.3

Pressure vs. Current

Due to synchrotron radiation driven gas desorption, the average pressure is a linear function of the total beam current. Values for total current and average pressure were extracted from all measurements done during one shift, plotted and fitted by a straight line. Results:

$$\begin{aligned} \text{Series 1} \quad P[\text{pbar}] &= 5.19 + \frac{I[\text{mA}]}{64.6} \\ \text{Series 2} \quad P[\text{pbar}] &= 5.11 + \frac{I[\text{mA}]}{63.9} \\ \text{Series 3} \quad P[\text{pbar}] &= 4.97 + \frac{I[\text{mA}]}{57.9} \end{aligned} \tag{10}$$

These equations display the fitted average pressure as measured by the vacuum gauges. Between series 1 and 2 the titanium sublimation wires had been fired. Obviously they do not have much effect on the measured pressure, which was expected since these wires are far away from the gauges[10].

Figure 2 shows series 3 measurements and the fit from eq.2 proving reasonably well the linear behaviour, with slight saturation visible for large currents. However the Touschek beam from series 3.3 shows a steep increase above 2.2 mA of single bunch current. Perhaps this is due to microwave heating of the vacuum chamber by the wake field of the short, strong bunch train.

Elastic Scattering

If a scraper is moved into the beam elastic scattering will be dominant. According to eq.3 the product lifetime$\times$pressure should show a linear dependancy on the squared scraper distance to the final position for complete beam loss. As an example, figure 3 shows the data and evaluation for series 2.1. The ratio of the linear fit's slope to the theoretical slope from eq.3 provides a correction factor $\mathcal{P}$ to be multiplied with the measured average pressure in order to obtain the **true** average pressure. Results are given below:

$$\begin{aligned} &\text{Series 1.2} \quad (\chi^2/\nu = 0.35) \quad \tau_{\text{el}}[\text{h}] = \frac{0.05(\pm 0.17) + 10.3(\pm 0.6)(\Delta y[\text{mm}])^2}{P[\text{pbar}]} \to \mathcal{P} = 1.25(\pm 0.07) \\ &\text{Series 2.1} \quad (\chi^2/\nu = 0.48) \quad \tau_{\text{el}}[\text{h}] = \frac{0.02(\pm 0.01) + 14.8(\pm 0.4)(\Delta y[\text{mm}])^2}{P[\text{pbar}]} \to \mathcal{P} = 0.87(\pm 0.02) \\ &\text{Series 3.1} \quad (\chi^2/\nu = 0.86) \quad \tau_{\text{el}}[\text{h}] = \frac{0.04(\pm 0.02) + 19.3(\pm 0.3)(\Delta y[\text{mm}])^2}{P[\text{pbar}]} \to \mathcal{P} = 0.67(\pm 0.01) \end{aligned} \tag{11}$$

The results indicate that the true pressure was improving from one measurement to the next. This was expected for progressing from series 1 to series 2, since the titanium sublimation wires had been fired the

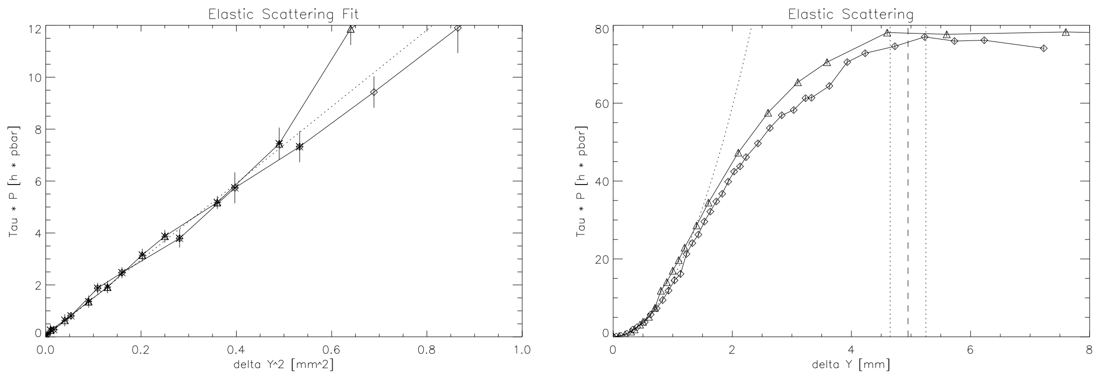

Figure 3: Series 2.1 scraper measurement of elastic scattering lifetime.

$\diamond$ vertical top scraper, $\triangle$ vertical bottom scraper.
left: $\tau \cdot P$ vs. Δy^2 plot, magnification of the linear region with points used for fit marked by asterisks and linear fit shown dotted.
right: $\tau \cdot P$ vs. Δy plot, full range. The linear fit appears as dotted parabola. The vertical acceptance of the machine is defined by the "shoulder" where the scraper just not yet affects the lifetime, i.e. where it still remains in the vacuum chamber aperture's shadow, and marked by the vertical dashed line with dotted parallels indicating the error estimate.

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day before taking series 2 data. The improvement seemed to continue still till series 3 which was taken one week later.

Scraper range

During taking series 2.1 using both bottom and top scrapers, the scraper driving ranges where checked and found to be 25.28 mm (top), resp. 25.70 mm (bottom). Total beam loss occured when driving in the scraper by 13.11 mm (top), resp. 13.10 mm (bottom). The full range was measured by driving both scrapers in until they had contact and found to be 27.59 mm. This leaves a gap of 1.38 mm for the beam itself. If this gap is identified with a $\pm 7\sigma$ beam stay clear to avoid quantum life time to become dominant, the emittance ratio of the beam would be g=25%, which definitely is excluded by other measurements (see below). Probably the missing millimeter is due to longitudinally slightly slanted scraper blades blocking the beam completely before having physical contact and due to some tolerances in the motor gears[11].

Vertical acceptance

For further lifetime studies, the storage ring's vertical acceptance has to be known in order to correctly subtract the elastic scattering contribution from the total lifetime, leaving the sum of Touschek and bremsstrahlung.

Fig. 3(right) shows the series 2.1 measurement with the fit appearing as parabola. Opening the scraper further and further, the lifetime would raise asymptotically to a value given by bremsstrahlung und Touschek, however, much earlier the curve is clipped by the vertical acceptance of the ring vacuum chamber. Thus the point where the scraper shows no effect, i.e. disappears in the vacuum chamber's shadow, defines the vertical acceptance. This point is indicated by the vertical dashed line. The acceptance then is obtained with the betafunction at the scraper, which is well known (→table page 1). Results:

$$\begin{array}{llll} \text{Series 1.2} & A_y & \approx 2.3 & \text{mm·mrad} \\ \text{Series 2.1} & A_y & = 3.2\ (\pm 0.4) & \text{mm·mrad} \\ \text{Series 3.1} & A_y & \approx 0.96 & \text{mm·mrad} \end{array} \tag{12}$$

Most care for vertical acceptance determination was taken in series 2.1. Nevertheless, the value in series 3.1

is surprising: It seemed at first, that the scraper was "hanging", however the value was confirmed by other means: We may exploit the fact, that in the extrapolation to zero bunch current, lifetime consists only of elastic scattering and bremsstrahlung: For bremsstrahlung lifetime the *theoretical* formula from eq.5 may be used after at least roughly estimating the effective energy acceptance. For extrapolation to zero current, the result of a linear fit to Touschek lifetime as a function of single bunch current may be used as described later. Evaluation of this kind could found a significant value only in the series 3 measurements:

$$\text{Series 3.3} \qquad A_y = 1.0\ (\pm 0.4)\text{mm}\cdot\text{mrad} \tag{13}$$

This value confirms the value observed for the onset of scraping, eq.12.

All acceptance values observed are lower than expected: In the present lattice configuration the 9L vacuum chamber limits the vertical acceptance to 5.5 mm·mrad (as long as U24 is not closed). The series 2.1 scraper value could be compatible with this if we assume some offset between scraper axis and 9L chamber axis. The too low values in series 3.1 and 3.3 are not yet understood.

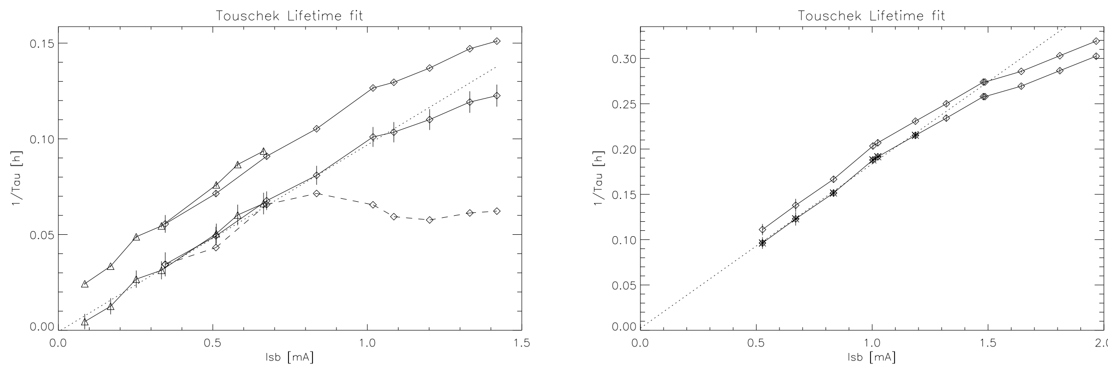

Figure 4: Inverse lifetime vs. single bunch current

left: ◇ series 1.3, △ series 1.4 total lifetime (upper lines) and after subtraction of elastic scattering assuming 3.9 mm·mrad of vertical acceptance. Dashed line: scaling by pinhole measured beam sizes.
right: ◇ series 2.2, points used for fit overplotted by asterisks. Elastic scattering subtraction for 3.2 (±0.4) mm·mrad vertical acceptance from eq.12.
Dotted lines show linear fits for Touschek lifetime according to eq.14.

Touschek Lifetime vs. Single Bunch Current

Linear fits were done for inverse touschek lifetime as a function of single bunch current after subtraction of elastic scattering lifetime. Fortunately, the uncertainty in vertical accceptance mainly affects the intercept of the linear fit containing the bremsstrahlung contribution, and not the slope, which has to be compared to eq.6. Figure 4 shows the measurements 1.3+4 and 2.2; 3.2 is not shown. Results for Touschek lifetime vs. current:

$$\begin{aligned}
\text{Series 1.3+4} \quad (\chi^2/\nu = 0.35) \quad \tau_{\text{ts}}\ [\text{h}] &= \frac{10.3\ \ (\pm 0.4)}{I_{\text{b}}\ [\text{mA}]} \\
\text{Series 2.2} \quad (\chi^2/\nu = 0.62) \quad \tau_{\text{ts}}\ [\text{h}] &= \frac{5.5\ \ (\pm 0.3)}{I_{\text{b}}\ [\text{mA}]} \\
\text{Series 3.3} \quad (\chi^2/\nu = 0.53) \quad \tau_{\text{ts}}\ [\text{h}] &= \frac{11.49\ (\pm 0.12)}{I_{\text{b}}\ [\text{mA}]}
\end{aligned} \tag{14}$$

Comparison of these results with eq.6, which was based on simulations assuming 2.0 MV of RF voltage providing 3.24 % of energy acceptance, tells, that either the emittance coupling is much less than 1 %, or that the energy acceptance is not limited by the RF but by something else.

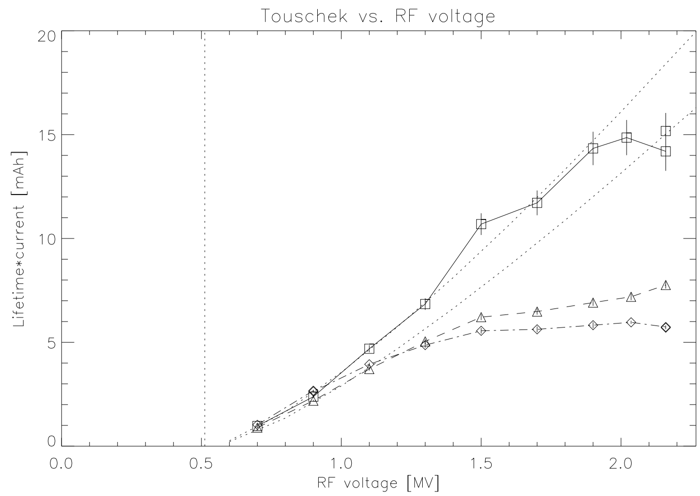

Figure 5: Touschek lifetime (normalized to single bunch current) vs. RF voltage

◇ series 2.3b, △ series 2.3a, □ series 3.2. Elastic scattering using acceptance estimates from eq.12 was subtracted. The vertical dotted line corresponds to the energy loss per turn U_o of 512 keV. The dotted curves correspond to scalings of tracking results from eq.6 for emittance ratios of 0.6 % (upper curve), resp. 0.4 % (lower curve). Voltage values were shifted down by 0.1 MV for optimum overlap with curves ("manual fit").

The hypothesis that Touschek scattered particles are lost at the vertical acceptance limitation, which was, according to simulations [3], a problem for the initial D2A lattice (working point 20.82/8.28) was excluded by the simulation shown in fig. 1 (right), where large rms roll errors were applied to force large emittance coupling: All seeds still follow the dotted $\tau_{\mathbf{ts}} \propto \sqrt{g}$ line, indicating no losses at the vertical acceptance limits.

Another possibility to explain bad lifetime, that the four cavity voltage vectors were not parallel, thus providing reduced sum voltage and energy acceptance, was largely excluded by adjusting the phases to balance the reflected power figures. The residual uncertainty on the total voltage thus was estimated to be within $-10/+0$ % [12].

Touschek lifetime vs. RF voltage

Touschek lifetime is a steep function of the available energy acceptance. For low RF voltage values, the energy acceptance is fully determined by the RF. At higher voltage, the energy acceptance of the lattice takes over smoothly and the lifetime gain from voltage increase is reduced [2]. At very high voltage, the acceptance is fully determined by the lattice and further voltage increase will only decrease the lifetime due to reduced bunch length.

Fig. 5 displays voltage measurements from series 2.3 and 3.2 and manual scalings of the tracking based predictions from eq.6. Note, that these scalings already include the smooth take over by lattice energy acceptance! Thus deviations of measured curves point to mechanisms not included in tracking.

For series 2.3 a breakdown of energy acceptance occurs already around 1.3 MV, corresponding to approx. 2.1 % of energy acceptance, with significantly lower lifetime for high chromaticity (2.3b). For series 3.2 the breakdown occurs at 1.9 MV, corresponding to 3.1 % of energy acceptance.

The reason for the different behaviour was found: Series 2.2 and 2.3 were measured at the nominal working point of 20.38/8.16 (D2R optics), series and 3.2 and 3.3 were measured at 20.42/8.19. This also explains the factor 2 difference of lifetime results in eq.14 (The working point for series 1.3. was not recorded.)

The tracking results shown as dotted curves in fig.5 were scaled by manually adjusting the emittance

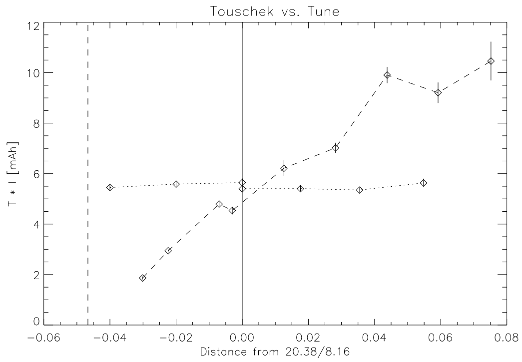

Figure 6: Touschek Lifetime vs. tunes
Series 3.4: dashed horizontal, dotted vertical tune change. Changes are relative to the nominal working point 20.38/8.16. The dashed vertical line indicates the resonance $3Q_x = 61$.

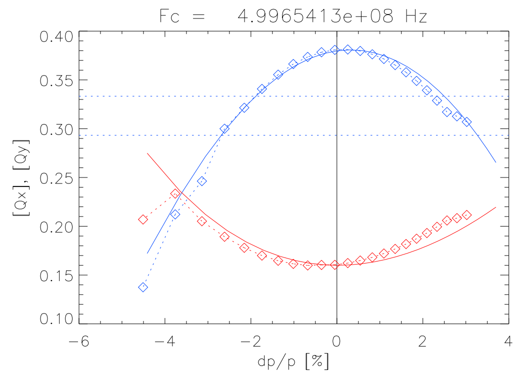

Figure 7: Tunes vs. energy deviation
Fractional tunes as a function of relative momentum deviation. Solid lines: simulation, ◇: measurements, upper curve is horizontal. Upper dotted horizontal line indicates the $3Q_x = 61$ resonance, lower where it is relative to beam when moving the tune to $Q_x = 20.42$.

ratio g for best overlap with the low voltage region of the measurements, where the RF energy acceptance certainly dominates. For series 2.3 a value $g = 0.4$ % was found to agree best, for series 3.2 it was $g = 0.6$ %. (It is quite possible that the emittance ratio could be that different due to the different working points.)

Touschek lifetime vs. betatron tunes

The strong tune dependancy of lifetime lead to the suspicion, that a nearby resonance is limiting the energy acceptance and thus to another measurement, shown in fig.6: While lifetime is independant of the vertical tune, we see a strong effect when changing the horizontal tune, which is proportional to the distance from the non-systematic first order sextupole resonance $3Q_x = 61$.

On this resonance, beam lifetime is known to be nonzero but very short: experience tells, that the machine can "jump" across with virtually no losses, if the tune is changed in a single large step (e.g. from 20.38 to 20.28), but operation close to the resonance ($|\Delta Q_x| < 0.03$) is impossible.

The second order chromaticity of the SLS TBA-lattice with dispersion free straights is rather large and difficult to suppress. This problem was discovered and acted upon already in early design works [7]. Measurements done earlier and shown in fig.7 confirmed exactly the predictions. As to be seen from the figure, for the nominal tune of $Q_x = 20.38$, particles with energy deviations of approx. 2 % reach the $3Q_x = 61$ resonance, whereas for $Q_x = 20.42$ approx. 3 % are tolerable. This explains the observations of Touschek lifetime and proves that the $3Q_x = 61$ resonance is responsible for the energy acceptance limitation.

Tracking studies could not reveal this effect, since only 1.5 synchrotron oscillations were tracked for reasons of computing time. Obviously the instability on the reasonance does not build up that fast, otherwise it probably would not be possible to jump across with the whole beam.

Turbulent bunch lengthening

The deviation of lifetime from the linear model in fig.4 deserves attention: Touschek lifetime scales with the bunch length. If we assume, that the deviation is due to a lengthening of the bunch, we may exploit the data to measure the longitudinal broad band impendance:

Fig.8 shows the ratio of measured Touschek lifetime to the linear fit – which is identical to the bunch lengthening paramter x – as a function of single bunch current I_b in double logarithmic scale. In the high

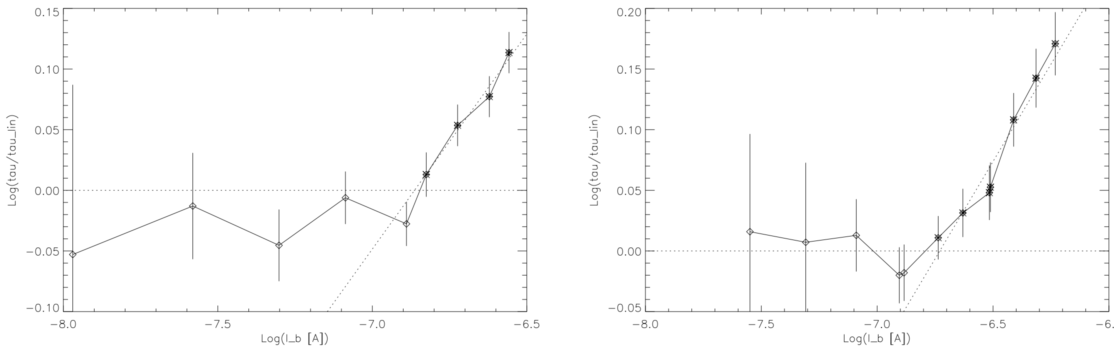

Figure 8: Indiciations of Turbulent Bunch Lengthening

Logarithm of the bunch lengthening paramter x (which is equivalent to the ratio of Touschek lifetime to linear fitted lifetime) vs. the logarithm of single bunch current. Dotted line shows the fit to determine bunch lenthening exponent and threshold current. left: series 1.4, right: series 2.2

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current regime, a linear fit (dotted line) gave the result

$$\begin{array}{lll} \text{Series 1.4} & (\chi^2/\nu = 0.2) & \ln x = 2.40\ (\pm 0.60) + 0.35\ (\pm 0.09) \ln I_b\ [\mathrm{A}] \\ \text{Series 2.2} & (\chi^2/\nu = 0.5) & \ln x = \underbrace{2.16\ (\pm 0.33)}_{B} + \underbrace{0.32\ (\pm 0.05)}_{A} \ln I_b\ [\mathrm{A}] \end{array} \tag{15}$$

Comparing to eq.9 we first notice, that the exponent of bunch length increase is compatible with the value 1/3 as predicted by theory. From the offset B and eq.8 we calculate longitudinal broadband impedance and TBL threshold current (the errors are so small due to a strong covariance between the A and B parameters):

$$\begin{array}{lll} \text{Series 1.4} & \left|\frac{Z_\parallel}{n}\right|_o^{\mathrm{bb}} = 241\ (\pm 13)\ \ \mathrm{m}\Omega & I_b^{\mathrm{th}} = 1.05\ (\pm 0.05)\ \ \mathrm{mA} \\ \text{Series 2.2} & \left|\frac{Z_\parallel}{n}\right|_o^{\mathrm{bb}} = 211\ (\ \pm 9\ )\ \ \mathrm{m}\Omega & I_b^{\mathrm{th}} = 1.19\ (\pm 0.05)\ \ \mathrm{mA} \end{array} \tag{16}$$

The two measurements are almost compatible. Weighted average gives $0.22\ (\pm 0.01)\ \Omega$ for the impedance and $1.12\ (\pm 0.05)\ \ \mathrm{mA}$ for the threshold current.

Surprisingly, there was no evidence for TBL in the series 3.3 measurement: Up to 3 mA Touschek lifetime vs. current was a straight line (beyond the beam became visibly unstable, and the lifetime even shorter). Whether this is due to the different tune or chromaticity settings compared to the other measurements, requires further investigation.

Spin polarization

Touschek lifetime also depends on the polarization state of the beam: According to theory, the beam in SLS will build up a maximum spin polarization level of 92% at a time constant of 1890 s [9] and thus increase the Touschek lifetime by approx. 10 %. In fact, slow positive drifts of lifetime were observed and mainly considered as disturbance of our measurements.

Measurements done in conjunction with our measurements (to be described later [6]), detected polarization build-up of 79 % at a time constant of approx. 1500 sec with the nominal optics at $Q_x = 20.38$. At $Q_x = 20.42$ no effect was found. This is probably due to the fact that the horizontal fractional tune coincides with the spin-tune, which is at 5.445 (theory), and thus destroys any polarization immediately.

Since the turbulent bunch lengthening was seen only at $Q_x = 20.38$ but not at $Q_x = 20.42$, the question has to be raised, if we really saw TBL or if the relative lifetime increase with current is due to a polarization process evolving during the measurements: The measurement series started with low current and proceeded

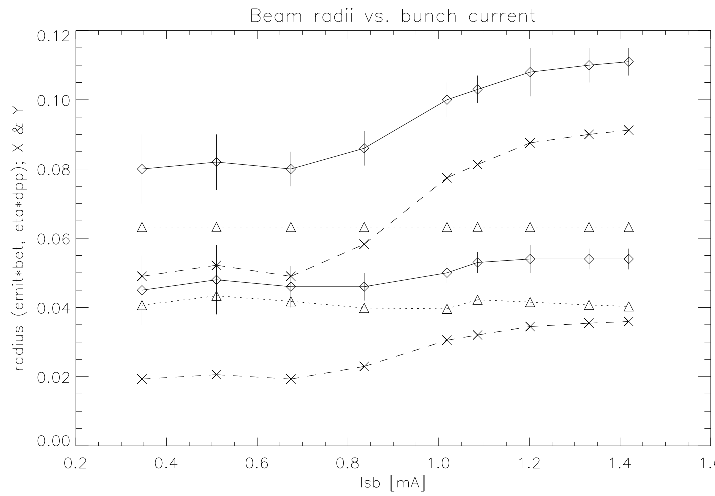

Figure 9: Series 1.4 pinhole measurement of beam radii

$\diamond$, solid: measured radii, upper horizontal, lower vertical.
$\triangle$, dotted: emittance and betafunction contributions.
$\times$, dashed: energy spread and dispersion contributions.

by adding some more after taking each data point. Taking the series took at least 30 minutes, which allowed the "old" parts of the beam to build up polarization in the meantime. Of course, it seems most unlikely that two independant measurements see fake TBL with the correct exponent. Probably more measurements and different procedures are required to confirm or disprove the evidence of TBL.

Pinhole measurements of beam radii

During series 1.4 also the beam radii were measured by means of the pinhole. The results are shown in fig.9: Obviously the beam sizes increase for single bunch currents above 0.8 mA.

If this is a true blow-up of the beam, the Touschek lifetime should scale correspondingly as shown in fig.4 (left, dashed curve). Certainly the figure disproves this hypothesis.

If we assume that the increase is related to an increase of energy spread due to turbulent bunch lengthening or something else, the emittance still has to be constant which is shown as the straight dotted line for the horizontal, leaving the dashed curve for the product of energy spread and dispersion. This in turn allows to fit emittance ratio and vertical dispersion to the vertical beam size. The results of the fit,

$$g = \epsilon_y/\epsilon_x = 2.3\% \qquad \eta_y = 1.7\text{cm}\,, \tag{17}$$

however, is incompatible with two independant measurements, which are compatible to each other:

1. The evaluation of Touschek lifetime as a function of RF-voltage indicated an emittance ratio in the order of $g \approx 0.4 \ldots 0.6$ %.

2. Earlier measurements on the off-energy difference orbit gave an rms vertical dispersion in the order of 5 mm and, by comparison with tracking studies, an emittance ratio in the order of $g \approx 0.5$ %.

Since the camera shutter averages over $1000 \ldots 3000$ turns, the hypothesis was discussed, that the pinhole image is blurred by some oscillation of the beam. However, up to 250 Hz beam stability in the few micron range was proven by spectra taken on turn by turn BPM data. Phase stability of the RF was measured to be well within 1° (pp) up to 100 kHz.

This problem is still open. At least, lifetime measurements confirm the suspicion, that the pinhole shows too large beam sizes.

Bremsstrahlung

Bremsstrahlung lifetime is left after subtraction of elastic scattering and Touschek lifetime from the total lifetime. The intercept of the straight line Touschek fits as shown in fig. 4 can be exploited either to determine bremsstrahlung lifetime, if a value for the vertical acceptance is available, or to determine the vertical acceptance, if we use the theoretical value of bremsstrahlung as input.

Here we obtained a significant value only in the series 3 measurements:

$$\text{Series 3.3} \qquad \tau_{\text{bs}} = 760\ (\pm 170)\text{h} \tag{18}$$

This value is not too far away from eq.5. Basically this result is the "inverse" of eq. 13.

Using the theoretical value for bremstrahlung lifetime from eq. 5 seems justified if the true pressure is known from elastic scattering measurements and the energy acceptance from Touschek measurements.

Combined Lifetime

The machine was operated on Dec. 17^{th} on the new working point 20.42/8.19. As an example we compare the measured lifetimes with the extrapolation from our fits, using the series 3 parameters for pressure, elastic scattering and Touschek from eqs.10,11,14 and the theoretical bremsstrahlung lifetime from eq.5:

350 mA in 390 buckets: $\tau_{\text{el}} = 12.8$ h, $\tau_{\text{bs}} = 43.5$ h, $\tau_{\text{ts}} = 12.8$ h $\rightarrow \tau = 5.5$ h. Measured: $\tau = 5$ h

130 mA in 390 buckets: $\tau_{\text{el}} = 19.5$ h, $\tau_{\text{bs}} = 66.5$ h, $\tau_{\text{ts}} = 34.5$ h $\rightarrow \tau = 10.5$ h. Measured: $\tau = 11.4$ h

Conclusions

- The pressure is a linear function of total beam current at least up to ≈120 mA.
- Beyond a single bunch threshold current of 2.2 mA an additional linear pressure increase starts, which is probably due to microwave heating of the vacuum chamber.
- The activity of the titanium sublimation wires is not visible in the pressure readouts.
- Elastic scattering lifetime shows good agreement with theory. Before activation of the titanium sublimation wires the true pressure is about 25 % higher than the measured one, afterwards it is about 25 % lower.
- Vertical acceptance is hard to determine. The most significant measurement gave 3.2 mm·mrad, which is only 60 % of the expected value.
- Touschek lifetime is very sensitive on the distance to the $3Q_x = 61$ resonance. Moving the horizontal tune from 20.38 to 20.42 is required to get almost out of reach.
- Emittance ratio observed from the relation of Touschek lifetime on RF voltage gave values of about 0.5 %. This is in agreement with earlier studies based on difference orbit measurements.
- Emittance ratio values obtained from the pinhole camera are too large.
- There are indications for turbulent bunch lengthening beyond a single bunch current of 1.1 mA, corresponding to 0.22 Ω longitudinal broadband impedance. Bunch length vs. current shows the power law with exponent 1/3 as expected.
- Spin polarization has been observed by Touschek lifetime increase.
- Extrapolated lifetimes based on the parameters from our fits can be extrapolated to other operating conditions and agree within 10%.

Outlook

More and improved measurements are required

- to improve precision in order to better determine the vertical acceptance of the machine, resp. the bremsstrahlung lifetime contribution,
- to suppress spin polarization from the Touschek lifetime measurements in order to extract cleanly turbulent bunch lengthening – if there is any,
- to understand why the pinhole shows too large beam size.

Even at the new tune of 20.42 the $3Q_x = 61$ resonance limits the energy acceptance and any RF voltage beyond 2 MV total is nothing but a waste of power. For that reason,

- the search for an even better tune should be continued,
- the $3Q_x = 61$ resonance (which is non systematic) should be supressed by improvements on lattice symmetry,
- and the second order chromaticity of the optics should be suppressed further.

Acknowledgement

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