

STUDY OF THE BEAM LIFETIME AT THE SYNCHROTRON LIGHT SOURCE DELTA

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Abstract

DELTA is a 1.5-GeV synchrotron light source operated by the TU Dortmund University. The beam lifetime, which is a critical issue for user operation of a light source, was studied experimentally and by simulation for different operation modes, i.e. single-bunch and multibunch fill patterns and for different beam currents. The electron loss rate is dominated by residual-gas scattering (Coulomb scattering and Bremsstrahlung) and by electron-electron scattering (Touschek effect). Since these processes depend in different ways on the momentum acceptance of the storage ring, a variation of the RF cavity voltage allows to disentangle their respective contributions to the total loss rate. The experimental results lead to a consistent picture for different operation modes with a characteristic dependence of the residual-gas pressure on the beam current.

INTRODUCTION

The 1.5-GeV electron storage ring DELTA is operated as a synchrotron light source and for accelerator physics studies by the Center of Synchrotron Radiation at the TU Dortmund University. DELTA provides a beam lifetime of approximately 12 h at 130 mA beam current in 144 bunches. This paper analyses the contributions of the major lifetime-reducing effects, namely the Touschek effect and residual-gas scattering.

When electrons collide either with electrons of the same bunch (Touschek effect) or electrons and nuclei of the residual gas, they may undergo a momentum change, which might exceed the RF momentum acceptance or, if the dispersive excursion is large enough, the electrons collide with the vacuum chamber. The position of the scattering event is crucial, since the dispersion at the scattering point determines the amplitude of the induced betatron oscillation and therefore the displacement of the electrons due to dispersion at other points in the storage ring. In the case of elastic scattering on the residual gas, the electrons experience an angular deflection. This induces a betatron oscillation which may also exceed the aperture given by the vacuum chamber.

The likelihood of an electron loss via Touschek effect increases with current density, while residual-gas scattering is the dominating effect in cases of poor vacuum.

THEORY

The beam lifetime τ is defined as

$$\frac{1}{\tau} = -\frac{dI/dt}{I}, \quad (1)$$

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Table 1: DELTA Beam Parameters

γ	Lorentz factor	2935
β_a	beta function at aperture	40 m
$\bar{\beta}_x$	average beta function	6.69 m
$\Delta p/p$	momentum acceptance	8×10^{-3}
σ_x	horizontal beam size (rms)	94 - 877 μm
$\sigma_{x'}$	horizontal angular spread (rms)	30 - 462 μrad
σ_y	vertical beam size (rms)	24 - 390 μm
σ_z	bunch length (rms)	11 mm $\hat{=} 37$ ps

the inverse relative decay rate of the beam current. Multiple decay rates add up to the total rate according to

$$\frac{1}{\tau} = \sum_i \frac{1}{\tau_i}. \quad (2)$$

The decay rate caused by elastic (el) and inelastic (inel) residual-gas scattering with either its nuclei (N) or electrons (e) is given by [1]

$$\frac{1}{\tau_S} = cn\rho \left(\sigma_{\text{el}}^N + \sigma_{\text{inel}}^N + \sigma_{\text{el}}^e + \sigma_{\text{inel}}^e \right), \quad (3)$$

with c being the speed of light in vacuum and n the number of atoms per molecule. The density ρ depends on the gas pressure p according to $\rho[\text{m}^{-3}] = 2.45 \times p[\text{hPa}]$. It shall be mentioned that p depends on the beam current I because of synchrotron radiation desorption. The respective expressions for the cross sections σ_{el}^N , σ_{inel}^N , σ_{el}^e , and σ_{inel}^e can be found in e.g. [1, 2]. They show dependencies on the momentum acceptance $\Delta p/p$, the atomic number of the residual gas Z and the beta function at aperture β_a .

The decay rate caused by Touschek effect is [2]

$$\frac{1}{\tau_T} = -\frac{N}{\gamma^2} \frac{r_e^2 c}{8\pi\sigma_x\sigma_y\sigma_z(\Delta p/p)^3} F(\eta) \quad (4)$$

with

$$\eta = \left(\frac{\Delta p/p}{\gamma\sigma_x} \right)^2, \quad (5)$$

r_e being the classical electron radius and N the number of electrons per bunch. The function F has to be calculated numerically and is only slowly varying. The other symbols are as defined in Tab. 1.

The Touschek effect shows a stronger dependence on the momentum acceptance $\Delta p/p$ than the residual-gas scattering which can be used to disentangle their respective decay rates by varying the RF voltage [3].

MEASUREMENTS

The lifetime was simulated using the above-mentioned relations for the Touschek effect and residual-gas scattering in order to obtain information on the various contributions to the measured lifetimes.

Measurements of the gas pressure as a function of the beam current were made to take the dependence on synchrotron radiation desorption into account. Since the number of gauges is insufficient to extract a reliable pressure profile, a position independent pressure with linear dependence on the beam current was assumed. A fit yields a pressure function according to

$$p = 7.39 \times 10^{-8} \text{ Pa} + I \times 1.48 \times 10^{-9} \text{ Pa/mA} . \quad (6)$$

In reality, local heating of the vacuum chamber due to wake fields as well as current-dependent orbit variations might cause a nonlinear dependence on I . For the evaluation of eq. 3 a pure N_2 gas load was assumed. Since the vacuum chamber cross section always exceeds $15 \sigma_{x,y}$, the quantum

lifetime is found to be irrelevant. The momentum acceptance of the RF bucket is below 1 %, while calculations have shown the momentum acceptance given by the aperture being larger than 1.78 %. Hence, the momentum acceptance is apparently dominated by the RF bucket.

Measurements have shown a constant bunch length independent of the single-bunch current up to 20 mA at DELTA. No signs of turbulent bunch lengthening were observed at the nominal electron energy [4].

The beam lifetime is measured by observing the change of beam current indicated by a current transformer. Measurements were performed under variation of the RF power. The corresponding RF momentum acceptance can be calculated analytically [5].

Results

Figure 1 shows the measured lifetimes in multibunch and single-bunch mode for different beam currents as a function of the momentum acceptance. Since the beam current decreases inevitably during each measurement, the quoted values of the beam current are averaged over the entire measurement period. For each data point the lifetime value is averaged over a period of approximately 2 minutes. The lifetimes are normalized to the maximum lifetime τ_0 at the largest momentum acceptance $\Delta p/p = 9.6 \times 10^{-3}$. In the

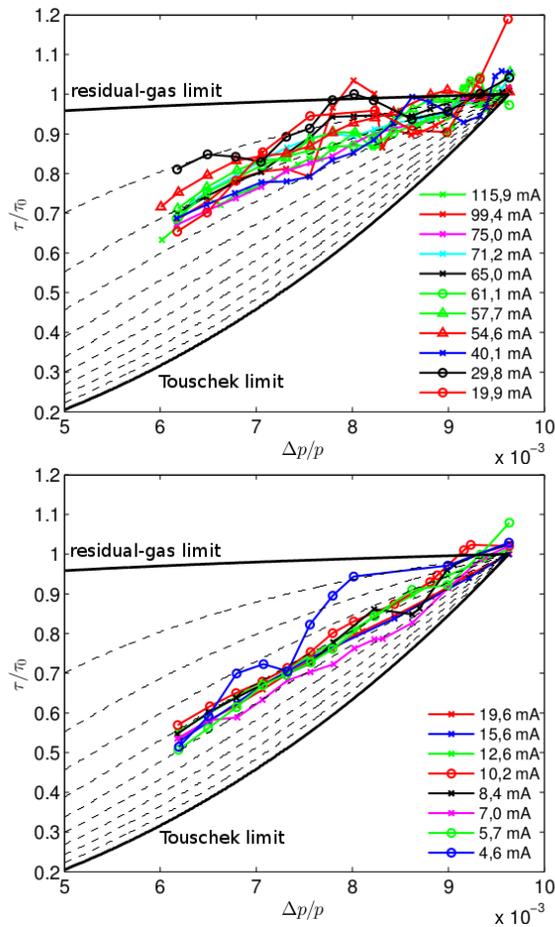


Figure 1: Normalized beam lifetime as a function of the momentum acceptance in multibunch (top) and single-bunch (bottom) mode for different beam currents. The dashed curves show the simulated lifetime changing the ratio between Touschek effect and residual-gas scattering in 10 % steps.

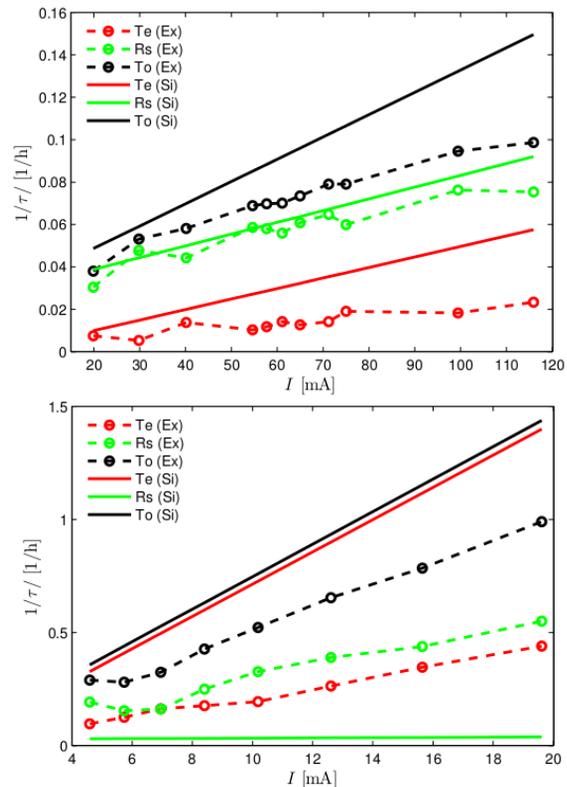


Figure 2: Calculated Touschek (Te), residual-gas (Rs) and total (To) loss rates of the measured (Ex) and simulated (Si) data as a function of the beam current in multibunch (top) and single-bunch mode (bottom).

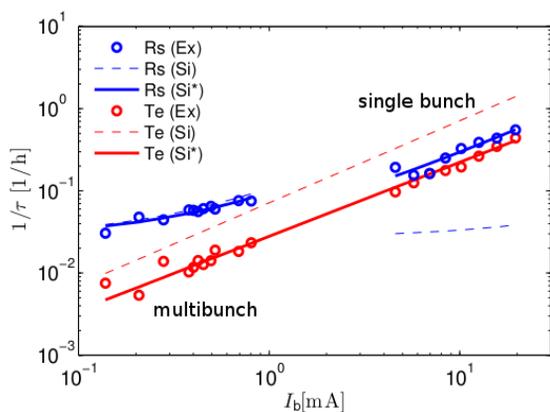


Figure 3: The decay rates of the Touschek effect (Te) and residual-gas scattering (Rs) as measured (Ex), simulated (Si) and of the modified simulation (Si*) as a function of the bunch current.

multibunch case, the lifetime is dominated by residual-gas scattering by about 80%. In single-bunch mode, the lifetime depends equally on both effects.

Figure 2 shows the simulated decay rates and those calculated from the data by fitting the individual contribution of the Touschek effect and residual-gas scattering to the curves in Fig. 1. While the simulated residual-gas scattering rates agree well with the measured data in multibunch mode, it was strongly underestimated in single-bunch mode. The assumed dependence of the pressure on the total beam current seems to be inaccurate. The simulation of the Touschek effect yields larger decay rates than measured in both operating modes.

Figure 3 shows the decay rates for a single bunch and multiple bunches as a function of the bunch current I_b in a common double-logarithmic plot. The disagreement of the simulated (red dashed line) and the measured (red dots) Touschek effect increases with the bunch current. The Touschek loss rate may be modified e.g. by potential-well distortion. Under the assumption of a I_b^α dependence with $\alpha \neq 1$, the Touschek loss rate of

$$\frac{1}{\tau_T} = 0.028 \frac{1}{h} \times \left(\frac{I_b}{\text{mA}} \right)^{0.9}, \quad (7)$$

results in a satisfactory agreement between simulation and measurement (red solid line).

In case of residual-gas scattering, the disagreement between simulation (blue dashed line) and measurements (blue dots) is assumed to be caused by the residual-gas pressure.

To obtain a better agreement (blue solid line), a pressure which has a linear dependence on the total current I as well as on the bunch current I_b was assumed. This dependence may be caused e.g. by wake fields heating the vacuum chamber. With this assumption, a new pressure function

$$p = 7.45 \times 10^{-8} \text{ Pa} + I \times 7.52 \times 10^{-10} \text{ Pa/mA} + I_b \times 7.09 \times 10^{-8} \text{ Pa/mA} \quad (8)$$

was determined.

It was tried to use scrapers to disentangle the Coulomb-scattering from the other gas-scattering cross sections since moving scrapers near the beam center reduces the momentum acceptance as well as the aperture [3]. However, the scrapers caused the pressure to rise to a point where reliable lifetime measurements were not possible.

CONCLUSION

At the electron storage ring DELTA, the lifetime was studied as a function of the RF momentum acceptance and beam current. Coulomb scattering was found to be the dominant effect in multibunch mode, while in single-bunch mode Touschek effect and Coulomb scattering contribute equally to the lifetime. The inconsistency of the gas pressure as function of single-bunch current deserves further investigation, taking into account a detailed pressure profile and the actual gas composition, both of which have been recently analyzed [6]. In addition, the bunch length and transverse size should be studied in order to understand the dependence of the Touschek effect on the bunch current I_b^α , since turbulent bunch lengthening was excluded.

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