LIFETIME STUDIES AT METROLOGY LIGHT SOURCE AND ANKA

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Abstract

The Metrology Light Source (MLS), situated in Berlin (Germany) is an electron storage ring operating from 105 MeV to 630 MeV and is serving as the national primary radiation source standard from the near infrared to the extrem ultraviolet spectral region [1]. In its standard user mode, the lifetime is dominated by the Touschek effect. Measurements and analysis of the Touschek lifetime as a function of beam current and RF-Voltage will be presented and compared to measurements done at the Ångströmquelle Karlsruhe (ANKA) electron storage ring (Karlsruhe, Germany) which operates at 0.5 to 2.5 GeV [2].

INTRODUCTION

To provide users of synchrotron radiation with temporally stable experimental conditions, the lifetime τ of the stored beam with current I is a parameter of concern. This is valid for machines with a decaying beam such as ANKA and MLS, but as well for machines operated in top up mode such as BESSY II in Berlin.

In 2012, the standard user operation at MLS yielded a lifetime of 3.5 hours at 150 mA beam current. Although reasonable due to the energy, this is a low value compared to 16 hours at ANKA and it would benefit the users of synchrotron radiation if it could be improved.

THEORY

There are two major loss mechanisms determining the lifetime of the electrons in an accelerator: The scattering of the electrons with residual gas atoms and the scattering of the electrons with other electrons within the bunch. The latter is known as the “Touschek effect”, named after Bruno Touschek who first observed the effect at the small AdA electron-positron collider. The two contributions are called gas lifetime and Touschek lifetime respectively.

The gas lifetime depends on the pressure P and a scattering cross section σ_{gas} for particle losses, for which the interested reader is referred to [5]:

$$\frac{1}{\tau_{\text{gas}}} \propto \sigma_{\text{gas}} \cdot P \,. \tag{1}$$

The cross section itself is a function of the acceptance of the accelerator $\delta_{\text{acc}} = \Delta p_{\text{max}}/p_0$, while the pressure P depends in some respect on the beam current.

The electrons in a bunch perform transverse betatron oscillations. Being an incoherent motion, this leads to Coulomb scattering. During the scattering process, transverse momentum gets transferred to longitudinal momentum. If the particles momentum deviation exceeds the momentum acceptance it will be lost. The resulting Touschek lifetime depends on the rate of scattering processes and therefore on the density within the bunch, i.e. on the bunch volume and the bunch current. Furthermore, it depends on the momentum acceptance with the power of three [5]:

$$\tau_{\text{T}} \propto \frac{\delta^3_{\text{acc}} \cdot \sigma_x \sigma_y \sigma_s}{N \cdot D(\xi)} \,, \tag{2}$$

with $\sigma_{x,y,s}$ being the rms-bunch sizes and length and $D(\xi)$ being a slowly varying function with respect to the acceptance δ_{acc}. D also depends on the optical functions around the ring through ξ.

The loss rates from Touschek effect and gas scattering add to the total loss rate $1/\tau$ which can be measured.

Multiplying the number of particles N (or the stored current I) to the Touschek lifetime τ_{T} results in a constant: $N \cdot \tau_{\text{T}} = \text{const}$. Therefore, when plotting $I \cdot \tau$ for a Touschek dominated lifetime a constant can be expected with respect to current.

Acceptance

Touschek lifetime and gas lifetime depend on the acceptance of the accelerator. Two acceptances are important here, and whichever is the smallest is the limiting one:

- RF-acceptance
- Geometrical acceptance.

The RF-acceptance $\delta_{\text{acc,RF}}$ approximately depends on the applied cavity voltage V as [4]

$$\delta_{\text{acc,RF}} \propto \sqrt{V} \,. \tag{3}$$

The geometrical acceptance depends on the minimal aperture of the vacuum chamber $a(s)$ and the dimensions of the beam. For MLS a first order approximation considering only the horizontal plane is:

$$\delta_{\text{acc,geom}} \approx \min\left[\frac{a_x(s)}{2D_x(s)}\right] \,, \tag{4}$$

with D_x being the horizontal dispersion function. In the upper plot of Fig. 1, geometrical and RF-acceptance are plotted with respect to the applied cavity voltage for MLS. At 310 kV cavity voltage, the RF-acceptance is no longer the limiting acceptance. From this value up to larger cavity voltages the geometrical acceptance is limiting.

Predictions

In the lower part of Fig. 1, the effect of the behaviour of the acceptances on the Touschek lifetime is shown for

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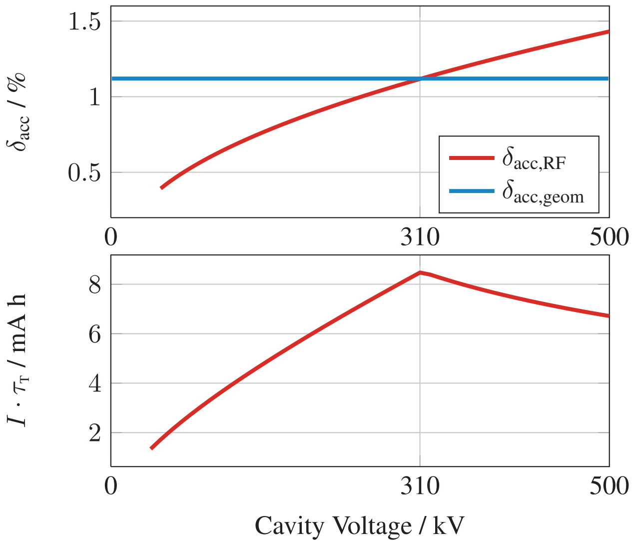

Figure 1: Top: RF-acceptance and geometrical acceptance for MLS in dependency of applied cavity voltage for the standard user mode in 2012. $\delta_{\mathrm{acc,geom}} = 1.1\%$ [3]. Bottom: Touschek lifetime for combined acceptances.

MLS. As the Touschek lifetime depends to the power of three on the acceptance and linearly on the bunch length (compare Eq. 2), the lifetime increases for increasing voltages up to 310 kV. From this value on to larger voltages the limiting acceptance does not increase any more, but the bunch length is still getting shorter. Therefore a decrease of Touschek lifetime to larger voltages is to be expected for MLS, where the geometrical acceptance is limiting. For ANKA, where the geometrical acceptance is not an issue in the voltage region tested, a steady increase of the Touschek lifetime is expected with increasing cavity voltage. In Fig. 2, the expected behaviour of the total lifetime, including Touschek lifetime and calculated gas lifetime, with respect to the applied cavity voltage is presented. For ANKA (top) the lifetime is expected to increase, for MLS (bottom) a peak lifetime at around 310 kV is expected. The gas lifetime was calculated as described in [3]. All calculations assume a single bunch current of 1 mA.

EXPERIMENT

In Fig. 3, the experimental results are presented for ANKA (top) and MLS (bottom). The product of bunch current and lifetime for 1 mA single bunch current is plotted against the applied cavity voltage. The upper part in Fig. 3 shows that the geometrical acceptance is not an issue for the voltages tested at ANKA. At MLS (lower part in Fig. 3) the behaviour is different. As predicted, current × lifetime increases with increasing cavity voltage up to a value of around 300 kV applied voltage. Further increasing the voltage leads to a decrease in current × lifetime. This states that the geometrical acceptance is the limiting acceptance for cavity voltages from a value of 300 kV to larger values for MLS.

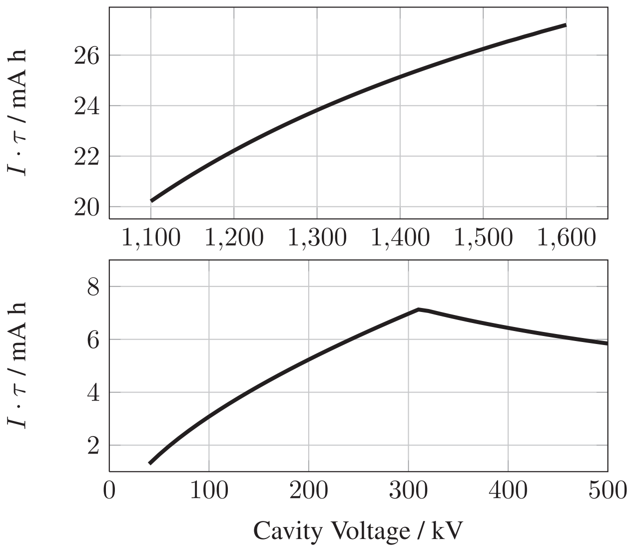

Figure 2: Predicted behaviour of the total lifetime with respect to cavity voltage for ANKA (top) and MLS (bottom).

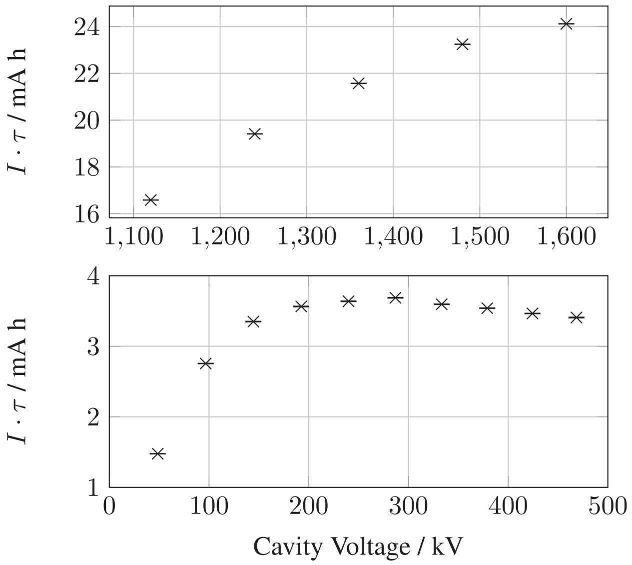

Figure 3: Single bunch current × lifetime against cavity voltage: (top) ANKA, 2.5 GeV; (bottom) MLS, 630 MeV. Single bunch current: $I_{SB} \approx 1$ mA.

LIFETIME IMPROVEMENT

The lifetime at MLS can be improved if the acceptance is only RF-limited even to larger voltages than 300 kV. To do so, the geometrical acceptance has to be improved.

In order to find optics with an increased Touschek lifetime, brute force optics scans using a Fortran code were performed [7]. Testing some of these new optics led to better understanding of the connection between the lifetime and the horizontal dispersion function at the place with minimum aperture (the septum, $a_x = 20$ mm).

In Eq. 4, the horizontal dispersion function D_x is in the denominator. By decreasing the dispersion function at the place with minimum aperture, the geometrical acceptance $\delta_{\mathrm{acc,geom}}$ can be improved. At MLS each quadrupole is powered independently. By tuning some quadrupoles of one family against the remaining ones of that family, the dispersion function was tuned to be zero at the septum. In Fig. 4, the dispersion function before and after the adjustments is presented. The septum, being the place with minimum aperture, is located at $s = 24$. Tuning the dispersion function led to a lifetime increase of 57 % [3].

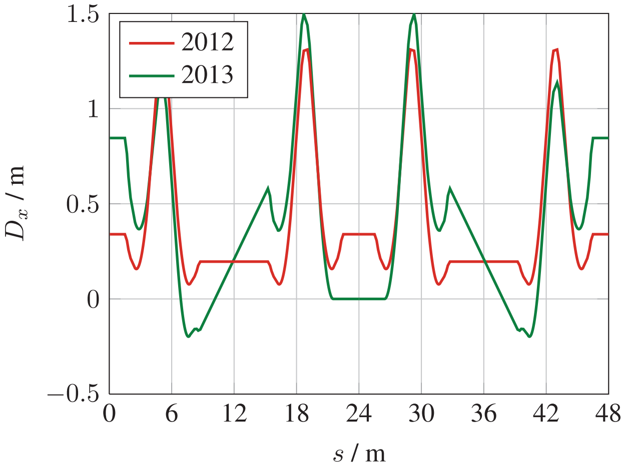

Figure 4: Change in dispersion function for the operation year 2012 and 2013 [3].

By carefully studying the orbit of the beam, it was noticed that the beam did not travel through the centre of the vacuum chamber at the septum at full energy. By recentring the beam at the septum using a beam bump, the aperture a_x could be further increased without rebuilding the existing vacuum chamber. Altogether, these adjustments led to an increase in lifetime of 80 %.

The peak lifetime with respect to cavity voltage is now located at 500 kV, being the maximum applicable cavity voltage at the moment. In Fig. 5, two multi bunch user operations are shown. Here the lifetime is plotted against the beam current and its increase becomes visible. The time that a current of 150 mA needs to decay to 80 mA increased from 3 h to 5 h. This new optics has been implemented as the new standard user optics since February 2013. Before the implementation, tests were performed to secure that the new optics do not negatively influence the performance at the beamlines.

The total lifetime increase is as high as 80 %. By solely increasing the acceptance, and the change in optical functions, the lifetime would have been expected to increase by about 30 %. An explanation for the additional increase could be a strong halo around the beam due to intra-beam scattering. With this, the effect of leading the beam through the centre of the vacuum chamber at the septum could be explained as well.

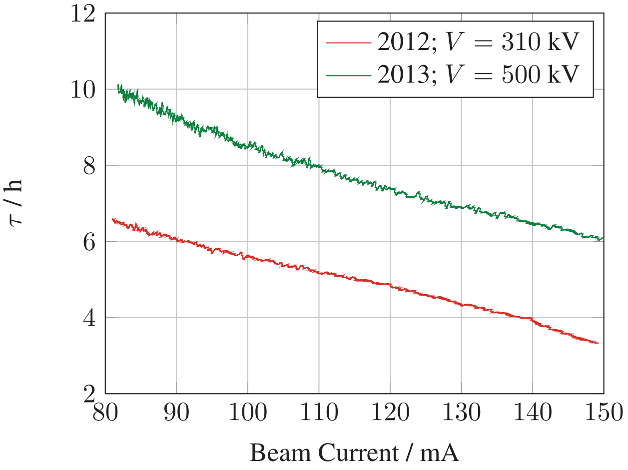

Figure 5: Lifetime with respect to beam current for standard user optics in 2012 and 2013 at MLS.

CONCLUSION AND OUTLOOK

The theory of the Touschek effect describes the dependencies on energy and acceptance well. By understanding the different loss mechanisms and the methods to manipulate the different acceptances, it was possible to generate a new user optics with an by 80 % improved lifetime. To completely explain the total lifetime increase, further measurements are needed.

To further increase the lifetime, alternate optics determined by optics scans will be tested [7]. Furthermore, the prospects of installing higher harmonic (“Landau”) cavities to lengthen the bunch, thereby reducing the bunch density i.e. the scattering rate, will be investigated. Also, the opportunity of controlling the emittance with the help of Robinson wigglers will be studied.

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