STUDIES OF THE ELECTRON BEAM LIFETIME AT MAX III

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Abstract

MAX III is a 700 MeV 3rd generation synchrotron light source located at the MAX IV Laboratory in Sweden. The lifetime in the storage ring is lower than originally envisaged. From vertical scraper measurements the lifetime contributions at 300 mA stored current have been determined. The lifetime is mainly limited by the Touschek lifetime, which is lower than its design value, whereas the vacuum lifetime is close to the expected value. The low Touschek lifetime is explained by a lower than design emittance ratio and momentum acceptance in the storage ring.

INTRODUCTION

The lifetime in MAX III is shorter than envisaged when the ring was designed. The origin of the short lifetime is investigated in this paper and in Ref. [1]. In this paper the focus is on measuring the different lifetime limitations contributing to the total lifetime in MAX III and comparing them to the design values.

The MAX III synchrotron light source [2] is intended for synchrotron radiation generation in the infrared and ultraviolet region. The storage ring makes extensive use of combined function magnets to obtain a compact lattice and a small 36 m circumference. It has an eightfold periodicity and each unit cell contains a dipole with a defocusing gradient and two focusing quadrupoles with a sextupole component.

The RF system in MAX III consists of three RF cavities: one active cavity and two passive higher harmonic cavities. The main cavity operates at 100 MHz and is actively powered by a FM transmitter. Two passive higher harmonic cavities, operating at 500 MHz and 300 MHz, are used to dampen longitudinal instabilities and to increase the bunch length in MAX III.

ELECTRON BEAM LIFETIME

The total lifetime in an electron storage ring is given by

$$\frac{1}{\tau} = \frac{1}{\tau_{elastic}} + \frac{1}{\tau_{inelastic}} + \frac{1}{\tau_{Touschek}} + \frac{1}{\tau_{quantum}} \quad (1)$$

where $\tau_{elastic}$ and $\tau_{inelastic}$ are the lifetimes due to the elastic and inelastic scattering of the beam electrons on the atoms of the residual gas, $\tau_{Touschek}$ is the lifetime due to electron-electron scattering and $\tau_{quantum}$ is the lifetime due to emission of synchrotron radiation.

The vertical scraper in MAX III can be used to determine the different lifetime limitations contributing to the total lifetime. The vertical scraper predominantly acts on electrons that have been elastically scattered on residual gas nuclei. At the location of the vertical scraper the vertical beam size is around 16 μm (one sigma). As long as the scraper is further away than 0.1 mm from the beam center the contribution of the quantum lifetime to the total lifetime is negligible. Inelastic scattering on the residual gas and the Touschek effect affects the energy of the beam electrons. If the vertical scraper affects the momentum acceptance it will also affect the inelastic scattering lifetime and Touschek lifetime. This could be the case, since electrons with large momentum deviation may transfer horizontal betatron motion into vertical. The momentum acceptance in MAX III can be determined by measuring the electron beam lifetime as a function of the main cavity voltage (see Ref. [1]). Measurements performed at different vertical scraper positions determined that as long as the scraper is 0.25 mm or further away from the beam center the momentum acceptance is not influenced. At 0.25 mm and further away, it is thus only the elastic scattering lifetime that is affected by the vertical scraper. Also, since the momentum acceptance is not affected, the position where the scraper becomes the vertical restricting aperture determines the vertical acceptance.

The elastic scattering lifetime for a one-dimensional vertically limiting aperture is given by [3]

$$\frac{1}{\tau_{elastic}} = cn_g \frac{2\pi r_e^2 Z^2}{\gamma^2} \left[\frac{\langle \beta_y \rangle \beta_y}{a_y^2} \right] \quad (2)$$

where c is the speed of light, n_g is the residual gas density, r_e is the classical electron radius, Z is the atomic number of the residual gas, γ is the relativistic factor of the electrons in the stored beam, $\langle \beta_y \rangle$ is the vertical beta function averaged over the storage ring, β_y is the vertical beta function at the limiting vertical aperture and a_y is the limiting vertical aperture. By combining Eq. 1 and Eq. 2 and measuring the total lifetime at different positions of the vertical scraper, a fit can be made on the data to determine the elastic scattering lifetime and the combined inelastic scattering and Touschek lifetime. The vertical acceptance a_y^2/β_y is constant until the scraper becomes the limiting aperture. When the scraper is the limiting aperture, a_y is the distance between the vertical scraper and the beam center and β_y is the vertical beta function at the vertical scraper. The design value for the vertical acceptance is 7.8×10^{-6} m and the design limiting vertical aperture is in the center of the dipole vacuum chamber.

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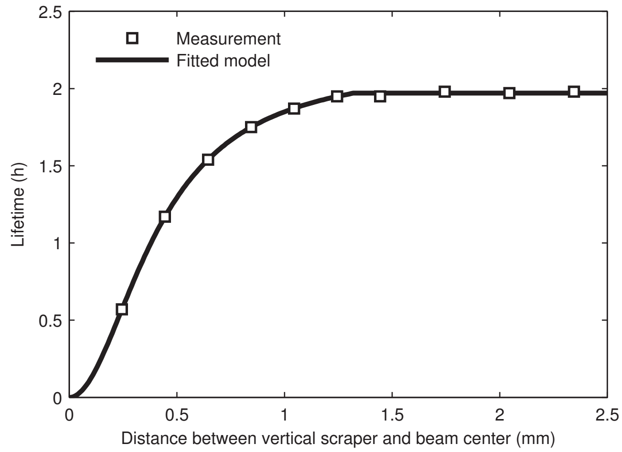

Figure 1: Vertical scraper measurement at around 300 mA stored current. Measurement of the lifetime in MAX III as a function of the distance between the vertical scraper and the beam center. The error of the measured lifetime is estimated to be smaller than $\pm 0.3\%$. The solid line corresponds to a fitted model to the measurement data.

If the residual gas composition is known, the residual gas density can be determined from Eq. 2. This can be used to determine the inelastic scattering lifetime. When the inelastic scattering lifetime is known the Touschek lifetime can be separated from the combined inelastic scattering and Touschek lifetime. This method was used to determine the lifetime limitations in MAX II [4, 5].

LIFETIME MEASUREMENTS

In MAX III in normal operating mode γ is 1370 ± 10, $\langle \beta_y \rangle$ is 4.478 ± 0.001 m and the vertical beta function at the location of the vertical scraper is 1.37 ± 0.01 m. Figure 1 shows a measurement of the lifetime in MAX III as a function of the distance between the vertical scraper and the beam center in April 2012. The main cavity voltage was 130 ± 1 kV and the stored current was around 300 mA. The RF frequency was 99.925 MHz, the 300 MHz Landau cavity resonance frequency was 300.193 ± 0.001 MHz and the 500 MHz Landau cavity resonance frequency was 500.328 ± 0.001 MHz. The measurement was performed after the realignment of the main cavity (see Ref. [1]). Figure 1 also shows the fitted model. Three different vertical scraper measurements with similar settings were performed during the same day. The mean and standard deviation of the elastic scattering lifetime for the three measurements is 22.3 ± 0.9 h and the corresponding result for the combined inelastic scattering lifetime and Touschek lifetime is 2.18 ± 0.01 h. The vertical scraper becomes the vertical restricting aperture at 1.35 ± 0.02 mm, which gives a vertical acceptance of $1.33 \pm 0.03 \times 10^{-6}$ m, much smaller than the design acceptance. The horizontal acceptance is larger than $44 \pm 2 \times 10^{-6}$ m [1], which makes the assumption in Eq. 2 of a one-dimensional limiting aperture valid.

Table 1: Comparison design and measured lifetimes. The design lifetimes are scaled to 300 mA stored current from [6], the measured lifetimes are for 300 mA stored current in April 2012.

	Design	Measured
Total lifetime (h)	8	1.98 ± 0.01
Elastic lifetime (h)	-	22.3 ± 0.9
Inelastic lifetime (h)	-	$\geq 147 \pm 8$
Vacuum lifetime (h) [a]	17	21 ± 2
Touschek lifetime (h)	15	2.20 ± 0.03
Momentum acceptance	0.020	0.0158 ± 0.0003 [1]
Emittance ratio	0.10	0.012 ± 0.001 [7]

[a] Combined elastic and inelastic lifetime

To separate the individual lifetime limitations from the combined inelastic scattering and Touschek lifetime the residual gas composition should ideally be known. Unfortunately, there is no good residual gas analyzer at MAX III. In MAX II the residual gas is dominated by H_2 [5] and the situation in MAX III is likely similar. However, for the particular situation in MAX III, it is possible to deduce the Touschek lifetime accurately even without any assumptions on the residual gas composition. The shortest inelastic scattering lifetime in MAX III would be for 100% H_2. The inelastic scattering lifetime would in that case be 147 ± 8 h for the three measurements. All other residual gas compositions give a longer inelastic scattering lifetime. Based on that information it is thus possible to determine that the Touschek lifetime is 2.20 ± 0.03 h.

In Table 1 the measured lifetimes are compared to the design lifetimes. The design Touschek lifetime was 4.5 Ah for an emittance ratio of 0.10. The design vacuum lifetime (the combined elastic scattering and inelastic scattering lifetime) was 2.6 Ah at start-up and 5.2 Ah after some years of operation [6]. The larger of these two design vacuum lifetimes is used in Table 1. Table 1 also includes the measured and design values for the momentum acceptance and emittance ratio. The measurement of the momentum acceptance is described in Ref. [1] and the emittance ratio was determined in Ref. [7]. The measured vacuum lifetime is somewhat larger than the design vacuum lifetime, in spite of the low vertical acceptance. This suggest a better vacuum in MAX III than what was expected during the design. The measured Touschek lifetime, however, is far from the design value. At current operating conditions, the MAX III lifetime is clearly Touschek limited.

THE TOUSCHEK LIFETIME

The design Touschek lifetime was envisaged to be achieved by a design with a Landau cavity to elongate bunches, a momentum acceptance of 0.020 and an emittance ratio of 0.10. The triple RF system of MAX III elongates the bunches, but the momentum acceptance as well as the the emittance ratio is smaller than design.

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In order to verify that the measured Touschek lifetime can be explained by the properties of the storage ring the linear Touschek lifetime has been calculated using OPA [8] and ZAP [9] for a fitted model of MAX III. For the settings used when measuring the lifetime limitations the calculated Touschek lifetime using OPA is 0.80 h, a factor of 2.7 smaller than the measured Touschek lifetime. The OPA calculation does not take the bunch lengthening from the Landau cavities and an increase in the energy spread from longitudinal instabilities into account. The energy spread and bunch length was measured during one of the vertical scraper measurements and a simulation of the triple RF system was performed. Using the measured energy spread together with the bunch shape and the small separatrix reduction resulting from the triple RF system, the Touschek lifetime was calculated using ZAP to be 2.8 h, a factor of 1.3 larger than the measured Touschek lifetime of 2.20 ± 0.03 h.

IMPROVING THE TOUSCHEK LIFETIME

The Touschek lifetime in MAX III would improve and come closer to the design value if the bunches could be elongated further or if the momentum acceptance or emittance ratio could be increased. During the lifetime measurement presented in this paper, the Landau cavities elongated the bunches. However, the 300 MHz cavity was not tuned in as far as it can be. By tuning in the cavity further, the Touschek lifetime can be increased by an additional 20%.

A realignment of the main cavity increased the momentum acceptance from 0.0116 ± 0.0003 to 0.0158 ± 0.0003 and doubled the Touschek lifetime [1]. The Touschek lifetime could be increased by an additional 50% if the lattice momentum acceptance was determined by the design apertures and the main cavity voltage was increased to 190 kV. The FM transmitter can give enough power to increase the main cavity voltage, but in order to increase the lattice momentum acceptance further investigations are needed to determine the origin of the restriction of the momentum acceptance.

The design emittance ratio was to be reached by increasing the coupling via a skew quadrupole located in the main cavity straight section. During normal operation the skew quadrupole is turned off, since engaging it decreases rather than increases the lifetime. When the skew quadrupole is turned off, the lattice momentum acceptance is determined by the horizontal apertures. When the skew quadrupole is engaged, the lattice momentum acceptance has been observed to instead be limited by the vertical apertures. In order to increase the lifetime by increasing the coupling, further investigations are first needed in order to locate the origin of the small vertical acceptance. Increasing the emittance ratio from the current value of 0.012 ± 0.001 to the design value of 0.10 would increase the Touschek lifetime by roughly a factor of three. Since the vertical beam size can not presently be increased through coupling, it is instead often increased during normal operation via excitation of the vertical tune. A signal generator connected to a strip line in MAX III excites the vertical tune, which increase the vertical beam size and the emittance ratio. This procedure increases the Touschek lifetime, but it makes the vertical beam size unstable and it is sensitive to shifts in the vertical tune due to movements of the gaps of the undulators. The measurements presented in this paper as well as the measurements presented in Ref. [1] were all performed with the vertical excitation disabled.

SUMMARY AND CONCLUSIONS

Vertical scraper measurements have determined the electron beam lifetime limitations in MAX III at 300 mA stored current. The elastic scattering lifetime is 22.3 ± 0.9 h, the inelastic scattering lifetime is larger than 147 ± 8 h, and the Touschek lifetime is 2.20 ± 0.03 h. No assumptions had to be made on the residual gas composition to determine the lifetime limitations. The vertical acceptance has been determined to be $1.33 \pm 0.03 \times 10^{-6}$ m. The vacuum lifetime is close to the expected value, whereas the Touschek lifetime is lower than foreseen. The low Touschek lifetime is explained by a lower than design emittance ratio and momentum acceptance in the storage ring.

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