BENCHMARKING OF TOUSCHEK BEAM LIFETIME CALCULATIONS FOR THE ADVANCED PHOTON SOURCE*

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Abstract

Particle loss from Touschek scattering is one of the most significant issues faced by present and future synchrotron light source storage rings. For example, the predicted, Touschek-dominated beam lifetime for the Advanced Photon Source (APS) Upgrade lattice in 48-bunch, 200-mA timing mode is only ~ 2 h. In order to understand the reliability of the predicted lifetime, a series of measurements with various beam parameters was performed on the present APS storage ring. This paper first describes the entire process of beam lifetime measurement, then compares measured lifetime with the calculated one by applying the measured beam parameters. The results show very good agreement.

INTRODUCTION

Many physical processes can cause particle loss from a stored beam, such as quantum effects, gas scattering effect, Touschek scattering effect, beam-beam collisions, etc. The total beam lifetime t is given by

$$\frac{1}{t} = \frac{1}{t_1} + \frac{1}{t_2} + \cdots \qquad (1)$$

where t_1, t_2,$\cdots$ are beam lifetime from each individual physical process. For a low emittance machine like the APS storage ring [1], compared to the Touschek scattering effect—which gives a beam lifetime ~ 10 hours when running at the 24-bunch, 100-mA mode–contributions from all other physical processes give a beam lifetime ~ 200 hours, which is negligible. This presents a great opportunity for benchmarking our Touschek beam lifetime calculation, which is a crucial topic for our future APS upgrade [2, 3].

The particle scattering rate depends on the bunch distribution, which is given by beam parameters and optical functions that vary with location s. Scattered particles with a larger momentum error may be lost due to large betatron and synchrotron oscillation amplitude. The boundary of momentum error acceptance is also localized, and is called a local momentum aperture (LMA) [4, 5].

In our experiment, the operational machine's optics are obtained from our regular LOCO fitting and optical correction [6] and the LMA is then calculated using `elegant` [7, 8] based on obtained machine models and rf voltage. Other beam parameters, such as bunch current, bunch length, beam size, and coupling, are varied and measured in the experiment. The Touschek lifetime T is then calculated by applying these measured parameters to the Piwinski's formula [9]. T is compared with measured beam lifetime $T_{meas.}$. Our experiment results show very good agreement, which makes us more confident on the simulated lifetime for our future APS upgrade.

LIFETIME CALCULATION

The local Touschek scattering rate R is given by Eq. (31) in Piwinski's paper [9], and is rewritten here:

$$R = \frac{r_0^2 c N^2}{8\sqrt{\pi}\beta^2\gamma^4\varepsilon_x\varepsilon_y\sigma_s\sigma_p} F(A, B, \delta_m), \qquad (2)$$

where r_0 is the classical electron radius, c is the speed of light, N is the number of particles inside the bunch, β and γ are relative velocity and factor, $\varepsilon_{x.y}$ are the transverse beam emittances, σ_s and σ_p are the bunch length and energy spread, and F is the factor depends on the local optical functions A, beam parameters B, and momentum acceptance δ_m. The Touschek beam lifetime T is given by the total beam loss rate, and is averaged over the ring:

$$\frac{1}{T} = \left\langle \frac{R}{N} \right\rangle. \qquad (3)$$

These calculations are performed with the program `touschekLifetime` [10], which conveniently reads required data from `elegant`.

MEASUREMENT OF INPUTS FOR LIFETIME CALCULATION

To validate Eqs. (2) and (3), optical functions and beam parameters should be known in advance and it is also preferable to vary beam parameters over a large range to check the equation's parameter dependency. In normal APS operation, the machine's optical functions are measured regularly and corrected to the designed model [6]. This corrected model is then used to determine the LMA from tracking with `Pelegant`, giving δ_m over the ring. Results show that the non-linear effects in the APS storage ring are well corrected and the LMA is only limited by the available rf voltage. Thus, the beam lifetime is measured under various conditions: including different bunch charge N; different beam size $\varepsilon_{x,y}$ through varying coupling; different bunch length σ_s, varied together with bunch charge and rf voltage and measured by a streak camera; and different momentum acceptance δ_m, through varying of rf voltage.

Calibration of rf voltage

To determine the actual rf voltage—as opposed to the nominal control system rf voltage readout (TotGapVolt)—we measured the synchrotron frequency (synchFreq) and

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compared it with the predicted synchrotron frequency (fs) from the nominal rf voltage, see Fig. 1. Though a large measurement noise had been observed, the trends between the measured and calculated synchrotron tunes agree very well, the nominal rf voltage is then used directly in the beam lifetime calculations.

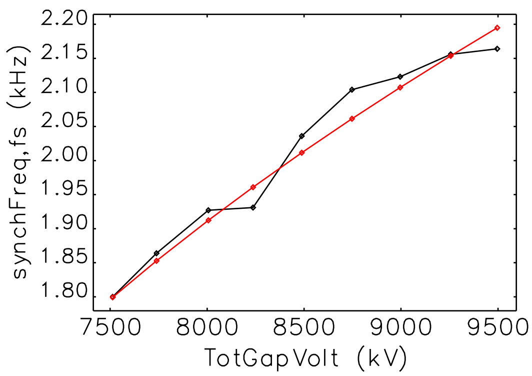

Figure 1: Measured (black) and calculated (red) synchrotron frequency vs the nominal rf voltage.

Bunch length measurement

Bunch length σ_s at different bunch current and rf voltages was measured by a streak camera, see Fig. 2. The measurement background was removed carefully and the true rms value is used as bunch length instead of using a simple Gaussian fit. The measurement results have also been fitted into a bunch lengthening equation, as illustrated Fig. 3. This complete set of results is convenient for use in other applications besides the present effort. Our measuerment was made below the ~7 mA microwave instability threshold, therefore the energy spread σ_p is a constant value and is obtained from the linear optics calculation.

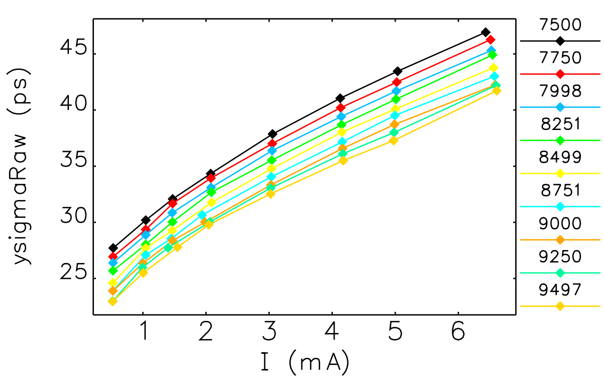

Figure 2: Measured rms bunch length vs bunch current at various rf voltage (legend in kV).

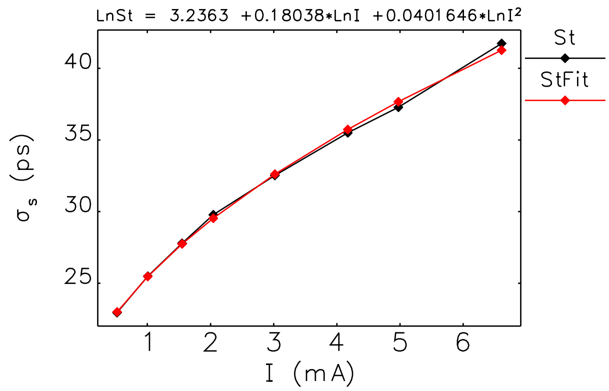

Figure 3: Measured and fitted rms bunch length vs bunch current at V_{rf} = 9500 kV.

Variation of other parameters

We have explained how to determine the local optical functions A, momemtun acceptance δ_m, bunch length σ_s, and energy spread σ_p in Eq. (2). The bunch charge N can be varied easily. To reduce measurement noise, beam was injected evenly into 24 bunches, so the measured lifetime will be an averaged value. The remaining beam parameters (also in B) are the transverse emittances $\varepsilon_{x,y}$. The natural beam emittance ε depends solely on the machine's optics, and can not be varied easily. Only the ratio of $\varepsilon_y/\varepsilon_x$ can be varied through coupling adjustment. In our experiment, we didn't intentionally change the coupling, but simply only recorded the horizontal and vertical beam size measured with a pin-hole camera, together with other beam parameters, see Fig. 4. One can see that the vertical beam size actually varies vs current and rf voltage, which is the result of some minor beam instability.

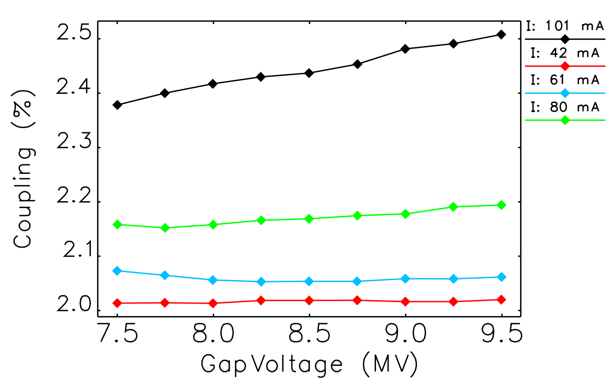

Figure 4: Measured coupling vs rf voltage at different total beam current (legend, in 24 bunch mode).

COMPARISON OF LIFETIME CALCULATIONS AND MEASUREMENTS

Beam lifetime $T_{meas.}$ was measured at different bunch current and different rf voltage, see Fig. 5. Other parameters in Eq. (2), $\varepsilon_{x,y}$, $\sigma_{s,p}$ and δ_m were derived from previous measurements shown in Figs. 2,3, and 4. Using the calibrated machine model [6], the theoretical Touschek beam lifetime T was calculated. The measured $T_{meas.}$ and calculated T beam lifetime are shown in Fig. 6, while the ratio $T/T_{meas.}$ is shown in Fig. 7.

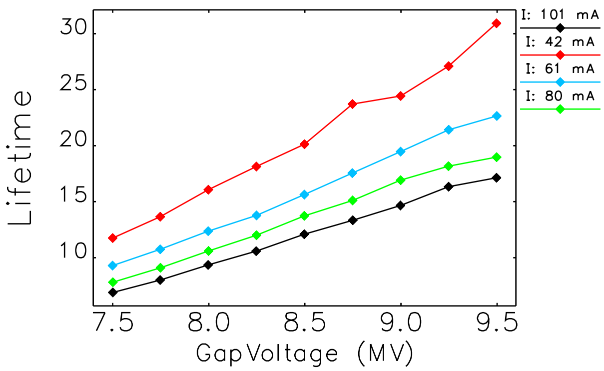

Figure 5: Measured beam lifetime vs rf voltage at different bunch current (legend, in 24 bunch mode).

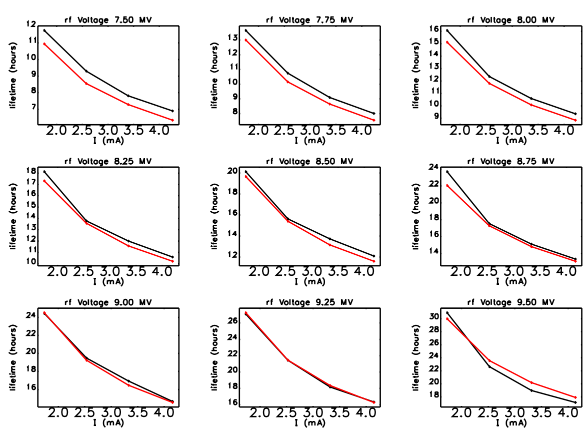

Figure 6: Measured (black) and calculated (red) beam lifetime vs bunch current at different rf voltage.

From Figure 7, we see a systematic error between measured and calculated beam lifetime vs rf voltage. We don't fully understand the reason, most likely it due to the rf voltage readout error which we don't have a good measurement on it, and/or some systematic error when doing bunch length measurement (background subtracting). Nevertheless, the agreement is still very good, and the calculated beam lifetime can be trusted.

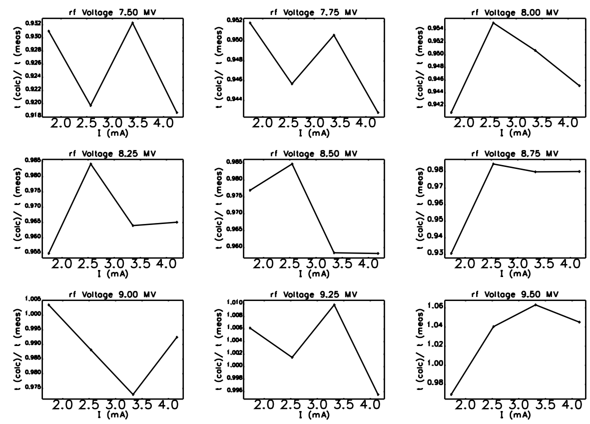

Figure 7: Ratio of $T/T_{meas.}$ vs bunch current at different rf voltage.

CONCLUSIONS

A complete set of beam lifetime measurements was made at the APS storage ring. Results show very good agreement between the measured and simulated beam lifetime, which gives us more confidence on the predicted beam lifetime for APS MBA upgrade design.

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