Momentum Acceptance of the SPring-8 Storage Ring

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Abstract

The momentum acceptance of the SPring-8 storage ring is studied through the Touschek lifetime. Investigating the dependence of the momentum acceptance on the operation point, the chromaticity and the gap height of an in-vacuum undulator, we deduce the possible model of limiting the acceptance. The simulation of the Touschek lifetime based on the model is compared with the measurement, which shows fairly well agreement.

1 INTRODUCTION

The SPring-8 storage ring, the high brilliant light source facility, has experienced the big optics change twice since the commissioning. The hybrid optics is the first one, whose horizontal beta function takes high and low values alternately at the dispersion free straight sections. The second optics is called the HHLV, whose horizontal and vertical beta functions take respectively high and low values at all the dispersion free straight sections. We call the present optics the LSS, which possesses four 30 m long magnet free straight sections. In September 1999, to make the straight sections with the low horizontal beta function fit for the undulators, the optics is changed from the hybrid one to the HHLV. The optics change surprisingly brought several times as large as the beam lifetime on the storage ring. Since the beam profiles, *i.e.* the natural emittance, the coupling ratio and the bunch length, were unchanged at the optic change, the growth of the beam lifetime is attributed to the enlargement of the momentum acceptance, which was indeed confirmed by the various machine study.

The beam lifetime is one of the most important parameters of the third generation light source facility. Hence, to understand the process of limiting the momentum acceptance, we investigated the beam lifetime under the various conditions at the SPring-8 storage ring. As the transverse dynamics severely affects on the momentum acceptance, we especially concentrate on investigating the dependence of the acceptance on the transverse optics parameters such as the operation point and the chromaticity.

On the other hand, there are in-vacuum undulators, which consist of movable arrays of magnets in vacuum vessel, installed in the SPring-8 storage ring. The vertical aperture then varies as the gap height of the in-vacuum undulators. To investigate the transverse dynamics of an stored particle of the SPring-8 storage ring, we studied the dependence of the momentum acceptance on the gap height of the in-vacuum undulator.

Considering the momentum acceptance measurements, we developed the model to explain the mechanism of the particle loss. A scattered particle by the residual gas or the intra-beam particles (Touschek effect) acquires the large momentum deviation which gives the tune shift due to the chromaticity. Furthermore, if the collision occurred at a dispersive section, the particle starts to oscillate with a large amplitude. Hence the particle suffers from the additional amplitude dependent tune shift, so that the motion could approach to a coupling resonance of the betatron oscillation. The vertical oscillation enhanced by the resonance leads to the particle loss and determines the momentum acceptance. The simulation of the momentum acceptance based on this scenario was carried out. The Touschek lifetime was estimated from the calculated acceptance, which agrees well with the experiment.

2 MEASUREMENT OF THE MOMENTUM ACCEPTANCE

Although the energy of the SPring-8 storage ring is relatively high, 8 GeV, the scattering by the intra-beam collision, the Touschek effect, has a significant impact on the beam lifetime due to the low emittance and the small coupling ratio. If high current is stored in a bunch, the Touschek lifetime dominates over other lifetime effects. By measuring the Touschek lifetime, we can estimate the momentum acceptance.

We measure the Touschek lifetime as a function of the rf voltage under different storage ring conditions with various horizontal tunes for constant vertical tune 21.36, which are shown in Figure 1. While the rf voltage is still increas-

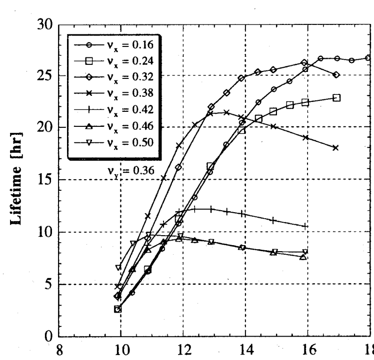

Figure 1: Beam lifetime as a function of rf voltage with different operation points.

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ing, the beam lifetimes cease to grow large. On the contrary, some of them with large horizontal tune decrease as rf voltage goes higher. The decrease tendency of the lifetime is understood by the fact that the bunch length becomes shorter as the rf voltage goes higher. These results suggest that the Touschek lifetime for high rf voltage is not limited by the rf bucket height but by the transverse aperture.

At the accelerating voltage 10 MV, the lifetime is considered to be determined by the rf bucket height. Hence the momentum acceptances at rf voltage 10 MV are all same breadths for different horizontal tunes. The difference of the beam lifetimes at 10 MeV is explained by the variation of the transverse beam sizes. In fact, the coupling ratio and then the transverse cross section vary as the distance from the differential resonance. In order to get rid of the effect due to the change in the transverse cross section, we normalize the beam lifetime by the value at rf voltage 10 MV. See Figure 2, where we also normalize the lifetimes by the bunch lengths which change corresponding to the accelerating voltage. In measuring the beam lifetime, we

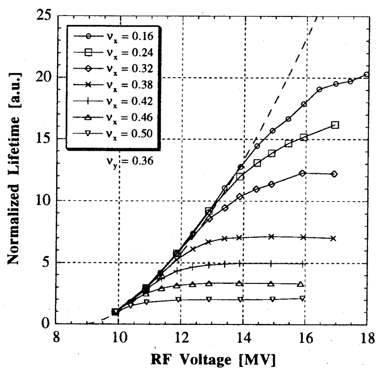

Figure 2: Normalized beam lifetime as a function of rf voltage with different operation points. The dashed line indicates the expected lifetime from the rf bucket height.

also measured the synchrotron frequencies to calibrate the rf voltage and the bunch length, whose results are shown in Figure 3. Note that the synchrotron tunes and hence the

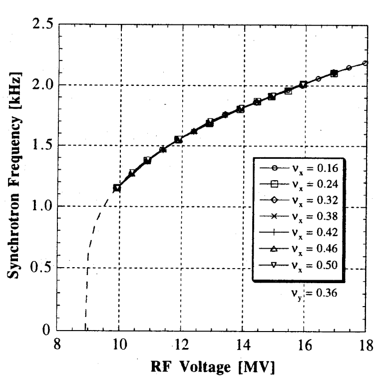

Figure 3: Synchrotron frequency as a function of rf voltage with different operation points. The dashed line indicates the expected bunch length from the rf bucket height.

bunch lengths do not depend on the horizontal betatron tune as expected.

As a result, we can conclude that the momentum acceptance is limited by the transverse dynamics. If the momentum aperture was determined by the rf bucket height or the physical aperture, the beam lifetime should be independent of the horizontal betatron tune.

Hence it is expected that the momentum acceptance depends on the chromaticity. We confirmed the prospect by measuring the Touschek lifetime for the cases with different chromaticities, whose result is shown in Figure 4. As

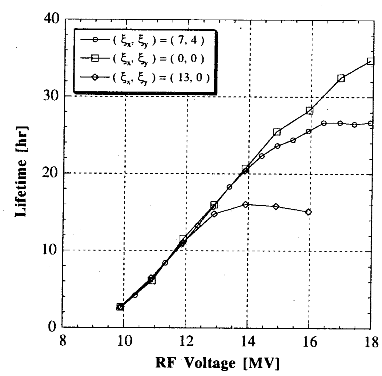

Figure 4: Beam lifetime as a function of rf voltage with different chromaticities.

expected the lifetime with the chromaticity (0, 0) is the longest for the large rf voltage.

To confirm that the particle is lost by the vertical aperture, we investigate the dependence of the Touschek lifetime on the gap height of an in-vacuum undulator, whose result is shown in Figure 5. As seen in Figure 5, under 10

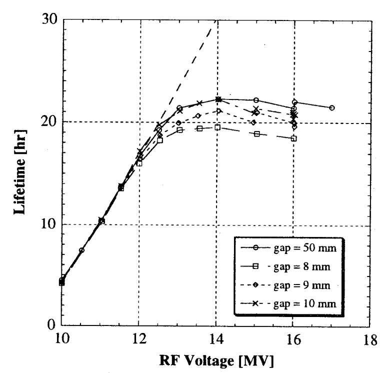

Figure 5: Beam lifetime as a function of the gap height of an in-vacuum undulator.

mm the momentum acceptance becomes as small as corresponding to the gap height.

3 A SIMPLE MODEL OF THE MOMENTUM APERTURE

The momentum aperture is determined by the longitudinal or transverse effect, *i.e.* the rf bucket height or the allowable transverse amplitude, respectively. The transverse motion of a particle is restricted by the physical and the dynamical apertures. After the collision of the Touschek effect at a dispersive section, an electron starts to oscillate with a big amplitude around the dispersive orbit. But it is enough large for the physical aperture that even an electron with quite large energy deviation is not lost by colliding with physical obstruction.

However the particle motion can reach the vacuum chamber aperture by resonantly developing oscillation. The tune shifts due to the momentum and the transverse deviations are approximated by

$$\begin{aligned}\Delta\nu_x &= \xi_x^{(1)}\delta + \xi_x^{(2)}\delta^2 + C_{11}\cdot 2J_x + \cdots, \\ \Delta\nu_y &= \xi_y^{(1)}\delta + \xi_y^{(2)}\delta^2 + C_{21}\cdot 2J_x + \cdots, \end{aligned} \qquad (1)$$

where $\xi_{x,y}^{(n)}$'s are respectively the n-th order chromaticities, $2J_x$ the horizontal emittances, and C's the coefficients of the amplitude dependent tune shift. In the Touschek effect, the oscillation is generated by the dispersive orbit jump due to the sudden energy change. Hence, we have

$$2J_x = \delta^2 H\left(s\right), \qquad (2)$$

with $H = \gamma\eta_x^2 + 2\alpha\eta_x\eta_x' + \beta\eta_x'^2$ and s the position where the collision occurs. Taking the small coupling ratio into account, we can ignore the vertical amplitude effect. The measured chromatic tune shifts in tune diagram, as well as the expected maximum tune shifts including the amplitude dependent tune shift, are given in Figure 6. Note that as where the collision occurs the tune shift varies along the circumference because the oscillation amplitude may change depending on the dispersion function. From Figure

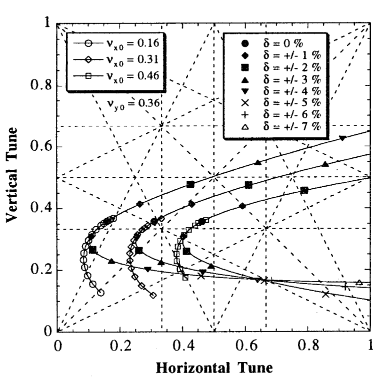

Figure 6: Tune diagram. The open symbols denote the measured chromatic tune shift. The solid lines represent the expected maximum tunes shifts taking the amplitude dependence into account. The resonance lines up to the third order are represented by the dotted ones.

6 we expect that particles going across the linear sum resonance will be lost. From the tune survey, we know that the other resonances crossing the tune shift curve ($\nu_x + 2\nu_y$ or the horizontal half integer resonances) do not kill particles.

4 SIMULATION OF THE MOMENTUM APERTURE

For the purpose of estimating the momentum acceptance, we perform the numerical simulation of the motion of the scattered electron based on the model presented in the previous section. As the ring model we use the error distribution obtained by the response matrix measurement [1]. In the simulation of the beam loss we find that the synchrotron oscillation and the radiation damping play very important roles. Taking in the synchrotron oscillation motion, we have developed the 6×6 orbit analysis code [2].

The Touschek lifetime is estimated by using the resultant momentum acceptance obtained by the simulation of the beam loss. In Figure 7, we show the comparison between the calculated and the measured lifetimes, which shows the fairly well agreement. This result convinces one that

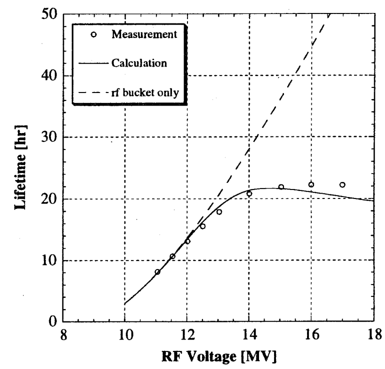

Figure 7: Beam lifetime as a function of rf voltage. Open circles denote the measured beam lifetime, the solid line does the calculated one. The dashed line represents the calculated lifetime without taking the transverse momentum acceptance into account.

the momentum acceptance of the SPring-8 storage ring is mainly determined by the transverse dynamics, or the coupling resonance.

5 CONCLUSION

It is clarified by the simulation that the momentum aperture of the SPring-8 storage ring is determined by the dynamical effect. In order to improve the lifetime dominated by the Touschek effect, one should take care of the higher order chromaticity and the amplitude dependent tune shift as well as the suppression of resonance excitation. Since we have already known the error distribution of the SPring-8 storage ring, it is planed to restore the optics to suppress the resonance excitation.

6 REFERENCES

[1] H. Tanaka, et al., in these proceedings.

[2] J. Schimizu, et al., in these proceedings.