TOUSCHEK LIFETIME AND MOMENTUM APERTURE OF THE SPRING-8 STORAGE RING

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Abstract

The momentum aperture of the SPring-8 storage ring is investigated through the Touschek lifetime. The measurement shows that the aperture depends on the horizontal betatron tune. The larger the horizontal tune becomes while keeping the vertical one constant, the smaller the aperture does. The possible explanation by a simple model based on a resonance excitation is given.

1 INTRODUCTION

The beam lifetime is one of the most important parameters for storage rings, especially dedicated to synchrotron light source. The SPring-8 storage ring is a high brilliant light source facility with the electron beam energy of 8 GeV, the stored current of 100 mA, the natural emittance of 6.2 nm-rad, and the coupling ratio below 0.1 %. Although the electron beam energy of the SPring-8 storage ring is considerably high, the low emittance and the small coupling ratio bring upon short Touschek lifetime [1], which becomes an issue particularly in the operation with high peak current.

In order to understand the mechanism limiting the beam lifetime, we perform various machine studies in Touschek dominant (high peak current) operation. In this paper we describe the results obtained through the machine studies.

2 HORIZONTAL TUNE SURVEY

The operation point of the SPring-8 storage ring is in the neighborhood of (43.16, 21.36). The differential resonance of $\nu_x - \nu_y \approx 22$ mainly contributes to the betatron coupling. As changing the horizontal tune while keeping the vertical one constant, we measure the beam lifetime in two conditions with accelerating voltages 12 MV and 16 MV, respectively. For the purpose that the Touschek effect dominates over other lifetime effects, we fill 21 equidistantly spaced buckets out of 2436 rf buckets with a high current (1 mA) per bunch.

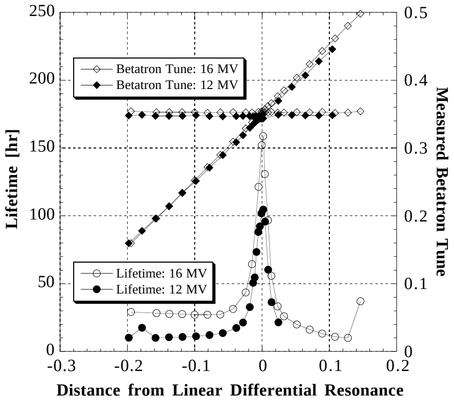

Figure 1: Measurements of beam lifetime as a function of detuning.

In the condition of rf voltage 12 MV the projection of the lifetime at the distance from the resonance -0.18 corresponds to the $2\nu_x - \nu_y$ resonance. (In measuring the lifetime with rf voltage 16 MV, we skip the point.) Similarly, the blowing up of the lifetime with 16 MV at the resonance distance 0.15 indicates the horizontal half integer resonance. Except the above characteristics, the most remarkable one is that away from the linear differential resonance the beam lifetime of 16 MV shows decreasing trend as the horizontal tune increasing. This fact strongly implies that the increment of the horizontal tune makes the momentum aperture small, since the bunch volume changes symmetrically with respect to the distance from the resonance and the bunch length scarcely depends on the distance. Hence we investigate the momentum aperture at the various operation points.

3 MEASUREMENT OF THE MOMENTUM APERTURE

Measurements of the Touschek lifetime as a function of the rf voltage were performed under different storage ring conditions with various horizontal tunes for constant vertical tune 21.36, which are shown in Figure 2. The beam lifetimes stop lengthening though the rf voltage still gains. Furthermore some of them having large horizontal tunes decrease as rf voltage goes higher.

Due to the betatron coupling the transverse section changes with the horizontal tune, which causes the change of the Touschek lifetime. Hence we normalize the lifetime at each operation point by the value at rf voltage 10 MV in order to get rid of the effect due to the change in the transverse section. See Figure 3. This procedure is justified by the facts that around the accelerating voltage 10 MV the beam lifetime increases according to the voltage development and that the momentum acceptance is then determined by the rf bucket only. In Figure 3 we also normalize the lifetimes by the bunch lengths which change corresponding to the accelerating voltage. At the same time we measured the synchrotron frequencies to calibrate the

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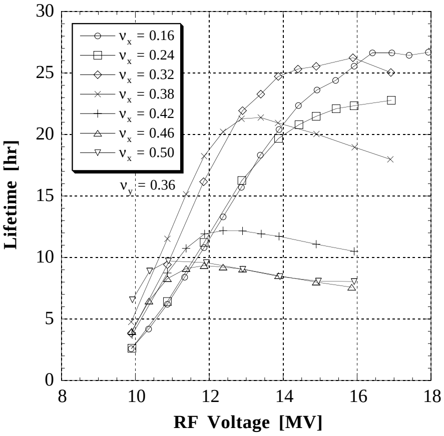

Figure 2: Beam lifetime as a function of rf voltage with different operation points.

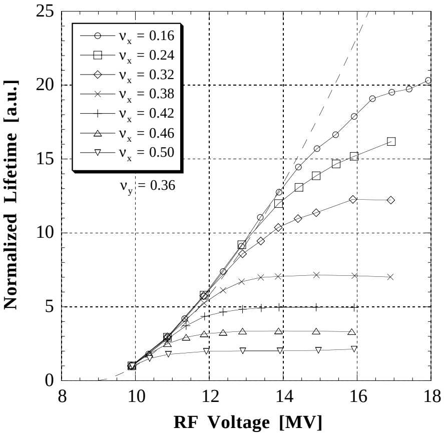

Figure 3: Normalized beam lifetime as a function of rf voltage with different operation points. The dashed line indicates the expected lifetime from the rf bucket height.

rf voltage and the bunch length, whose results are shown in Figure 4. Note that the synchrotron tunes and hence the 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.

4 A SIMPLE MODEL OF THE MOMENTUM APERTURE

Decking and Robin [3] gave the simple model of dynamic limit of the momentum aperture, which we apply to the case of the SPring-8 storage ring.

The momentum aperture is determined by the longitudinal or transverse effect, *i.e.* the rf bucket height or the allowable transverse amplitude, respectively. As well known

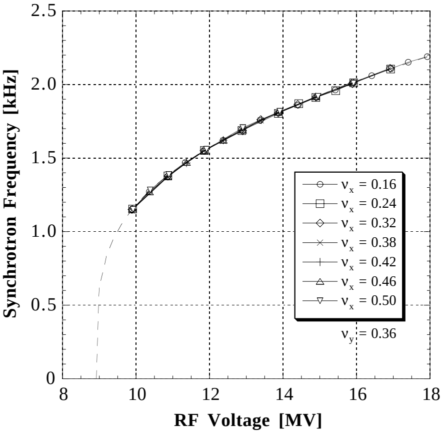

Figure 4: Synchrotron frequency as a function of rf voltage with different operation points. The dashed line indicates the expected bunch length from the rf bucket height.

the rf bucket height ϵ_{rf} is given by

$$\epsilon_{rf} = \sqrt{\frac{U_0}{\pi \alpha h E_0} F(q)}, \tag{1}$$

where U_0 is the radiation loss, α the momentum compaction factor, h the harmonic number, E_0 the nominal energy, and $F(q) = 2\left\{\sqrt{q^2-1} - \cos^{-1}(1/q)\right\}$ with the over voltage ratio $q = eV_{rf}/U_0$ (V_{rf}: the peak rf voltage).

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 point, an electron starts to oscillate with a big amplitude around the dispersive orbit. 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

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

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

$$2J_x = \delta^2 H(s), \tag{3}$$

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 betatron coupling 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 5. Note that the tune shift varies along the circumference because the oscillation amplitude may change depending on the dispersion function. From Figure 5 we expect that particles

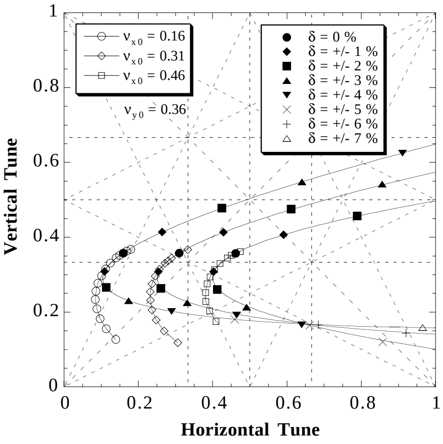

Figure 5: Tune diagram. The open symbols denote the measured chromatic tune shift. The solid lines represent the expected maximum tunes shifts taking the amplitude dependence into account. The resonance lines up to the third order are represented by the dotted ones.

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. Then, solving the linear sum resonance condition derived from the tune shifts by energy deviation (2), we get the dynamic momentum aperture

$$\delta_{\pm} = \frac{-\xi_{s1} \pm \sqrt{\xi_{s1}^2 + 4a\left(1 - \nu_{x0} - \nu_{y0}\right)}}{2a} \qquad (4)$$

with $\xi_{s1} = \xi_x^{(1)} + \xi_y^{(1)}$ and $a = \xi_x^{(2)} + \xi_y^{(2)} + (C_{11} + C_{21})\,H$. Here ν_{x0} and ν_{y0} are the central horizontal and vertical tunes, respectively. From Eq. (4) it is clear that the dynamic momentum apertures $\delta_\pm$ strongly depends on the betatron tune.

Using the above momentum aperture, we can calculate the Touschek lifetime [1]. Figure 6 shows the comparison of the measured and calculated results for the fractional tunes (0.16, 0.36). It should be emphasized that in the collision one electron gets momentum and the other loses same amount of momentum. Hence the total Touschek lifetime is the average of ones of the momentum apertures $\delta_\pm$, which is indicated by the dashed line in Figure 6. Although the model is very simple, the calculation of the Touschek lifetime agrees fairly well with the measurement.

The formula of the dynamic momentum aperture (4) implies that the larger the linear chromaticity becomes, the smaller the aperture does. We confirmed the prospect by measuring the Touschek lifetime for the cases with different chromaticities, whose result is shown in Figure 7. As expected the lifetime with the chromaticity (0, 0) is the longest for the large rf voltage.

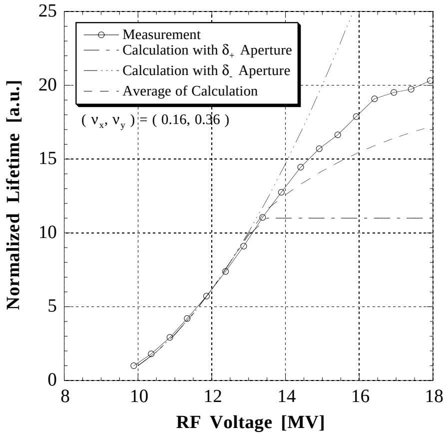

Figure 6: Normalized beam lifetimes as a function of rf voltage of measured and calculated.

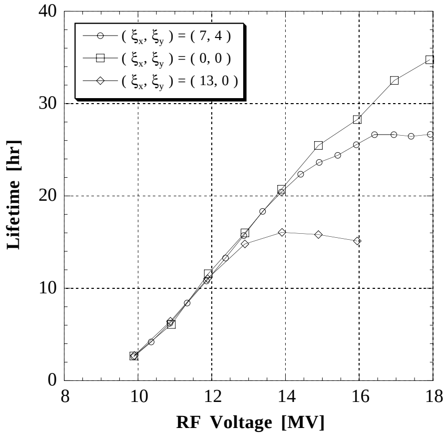

Figure 7: Beam lifetime as a function of rf voltage with different chromaticities.

5 CONCLUSION

It is clarified by the simple model 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 the higher order chromaticity and the amplitude dependent tune shift as well as the suppression of resonance excitation.

6 REFERENCES

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