ENERGY ACCEPTANCE AND TOUSCHEK LIFETIME CALCULATIONS FOR THE TPS STORAGE RING

H.J. Tsai*, H.P. Chang, M.S. Chiu, P.J. Chou, W.T. Liu,
G.H. Luo, C.C. Kuo, F.H. Tseng and C.H. Yang
National Synchrotron Radiation Research Center, Hsinchu 30076, Taiwan

Abstract

Touschek scattering is an important beam lifetime limiting effect for the TPS storage ring due to low emittance, small physical aperture and large second-order momentum compaction factor (nonlinear longitudinal motion). The Touschek relevant energy acceptance is determined by these factors; therefore a reliable estimate of the Touschek lifetime is essential. We obtained Touschek induced betatron oscillation amplitudes in three sections (LS, SS and ARC) and RF bucket acceptance analytically and with simulations. In this paper, we present the energy acceptance and Touschek lifetime calculations for the TPS storage ring in the cases for different chromaticity settings, ID chamber limitations, magnet multipole field errors and optics correction effects.

INTRODUCTION

Touschek lifetime is given as a function of energy acceptance (EA) and bunch volume integrated over the lattice structure. It can be expressed as

$$\frac{1}{\tau_{T1/2}} = \frac{\sqrt{\pi} r_c^2 c N C(\varsigma)}{\sigma_x^{'} \gamma^3 \varepsilon_{acc}^2 V} \tag{1}$$

Where $V=8\pi^{3/2}\sigma_x\sigma_y\sigma_L$, $\zeta=[\varepsilon_{acc}/\gamma\sigma_x']^2$, N is the number of electrons per bunch, ε_{acc} = EA, and

$$C(\varsigma) = -1.5e^{-\varsigma} + \frac{\varsigma}{2}\int_{\varsigma}^{\infty}\frac{\ln u}{u}e^{-u}du + 0.5(3\varsigma - \varsigma\ln\varsigma + 2)\int_{\varsigma}^{\infty}\frac{e^{-u}}{u}du \tag{2}$$

EA is determined by several aperture limits, i.e., non-linear longitudinal motion, RF bucket and transverse momentum acceptance.

Taiwan Photon Source (TPS) is a 3 GeV third generation synchrotron light source [1]. The emittance of lattice is 1.6 nm-rad with slightly positive dispersion in the straight sections. It is designed for low emittance with large chromaticity generated by the required focusing, and hence strong sextupoles for correction of large chromaticity are needed. The optimization of dynamic aperture using harmonic sextupoles is explored. Furthermore, the multipole magnetic field errors will cause reduction of dynamic aperture. The lattice has a large second-order momentum compaction factor. The first and second-order momentum compaction factors are $\alpha_1=2.4\times10^{-4}$ and $\alpha_2= 2.1\times10^{-3}$, respectively. Therefore the RF bucket is deformed due to non-linear longitudinal motion. Dependence of Touschek lifetime on the emittance coupling ratio and ID gaps are studied. 6-D EA tracking is implemented in the TRACY code. The resolution for tracking of local EA is 0.05%. To save computing time, we usually track the EA of one super-period except for the case of corrected IDs effect in this paper. The lattice parameters for Touschek lifetime calculation are listed in Table 1. The TPS Phase-I IDs are listed in Table 2. The EPU48s will be installed for a double mini-betay optics lattice [2]. The EPU48s are not included in this paper for Touschek lifetime calculation.

Table 1: TPS Storage Ring Parameters

Nominal Energy	3.0 GeV
Beam Current	400 mA
Circumference	518.4 m
Natural emittance	1.6 nm-rad
Cell units	24 DBA
Super-period	6
Radiofrequency	499.654 MHz
Harmonic number	864
RF voltage	3.5 MV
Straight section length*number	12m*6+7m*18
Betatron tune ν_x/ν_y	26.18 / 13.28
Momentum compaction (α_1, α_2)	2.4×10^{-4}, 2.1×10^{-3}
Natural energy spread	8.86×10^{-4}
Natural chromaticity ξ_x/ξ_y	-75 / -26
Bunch length σ_l	2.86 mm

Table 2: TPS Phase-I ID Parameters

ID name	Len (m)	Period (mm)	Gap (mm)	Chamber (mmxmm)	Number / Straight/VA
IU22	2	22	7	±34x±3.5	2 / SS / 5.43
IU22	3	22	7	±34x±3.5	3 / SS / 4.06
U50	3.9	50	20	±34x±6.5	1 / SS / 10.6
EPU48*	3.5	48	13	±34x±3.9	2 / LS / 1.41

NONLINEAR LONGITUDINAL MOTION

The longitudinal Hamiltonian is

$$H(\phi,\delta) = \omega_{rf}(\alpha_1\frac{\delta^2}{2} + \alpha_2\frac{\delta^3}{3}) + \frac{eV_{rf}}{E_0T_0}[(\cos\phi - \cos\phi_s) + (\phi - \phi_s)\sin\phi_s] \tag{3}$$

where V_{rf} is the RF voltage, ω_{rf} is the RF angular frequency, ϕ_s and ϕ are the RF phases of the reference and test particle respectively, E_0 is the particle energy and T_0 the revolution period. α_2 is an order of magnitude large than α_1 in the TPS design. The longitudinal phase space derived from Eq. (3) (blue line) and simulated by Tracy2.6 6-D tracking (red block) with 3.5 MV RF voltage and radiation damping is shown in Figure 1. The RF bucket centred around $\phi=\phi_s$, $\delta=0$ is asymmetric in energy, the upper limit is at 4.28% and the lower limit is at -6% in the analytical result. In the simulation, the upper limit is at 4.3% and the lower limit is at -6.1%. The bunch

---

*jacky@nsrrc.org.tw

length and RF bucket are determined by the RF gap voltage. Figure 2 shows the RF bucket momentum and bunch length as a function of RF gap voltage considering the second-order momentum compaction factor, simulated by Tracy 6-D tracking and calculated analytically, respectively.

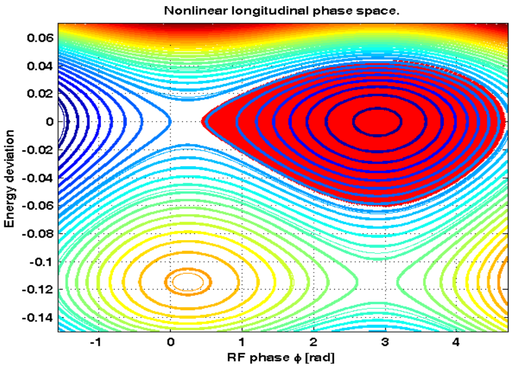

Figure 1: The nonlinear longitudinal phase space with 3.5MV RF voltage is shown. Red block is simulated by Tracy 6-D tracking and blue line is by Eq. (3).

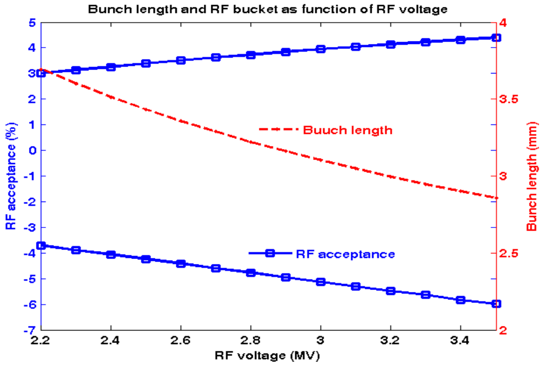

Figure 2: RF bucket as a function of RF voltage simulated by Tracy 6-D tracking is given in blue line. The analytical bunch length as a function of RF voltage is shown in red dash line.

TRANSVERSE MOMENTUM ACCEPTANCE

The envelope of the particle oscillation subsequent to a collision located at s* is given by

$$A_x(s,\delta) = \eta^1(s,\delta)\delta + \eta^2(s,\delta)\delta^2 + \sqrt{\beta(s,\delta)H(s^*,\delta)}\,\delta \qquad (4)$$

where $H(s^*,\delta) = \gamma(s^*,\delta)\eta^2(s^*,\delta) + 2\alpha(s^*,\delta)\eta(s^*,\delta)\eta'(s^*,\delta) + \beta(s^*,\delta)\eta'^2(s^*,\delta)$. The first and second terms in (4) are due to the chromatic closed orbit and the second order dispersion while the third term results from induced betatron motion. $A_y(s^*,\delta) = \kappa A_x(s^*,\delta) = \kappa/(1+\kappa)A_0(s^*,\delta)$, A_0 is the induced invariant amplitude without coupling, κ is the emittance ratio. Figure 3 shows the off-energy frequency map tracked with Tracy 2.6 in the presence of the multipole field errors, 1% emittance coupling, ID chamber limitations and for 3.5 MV RF voltage. The induced amplitudes at different locations are also shown in Fig. 3. In this case, the EA is dominated by transverse momentum acceptance. The similar results are shown in the energy acceptance tracking (see Fig. 4). There are around 4% positive energy acceptance for LS, SS and Arc sections. The negative energy acceptances are -5.7%, -5.7%, -3.7% for LS, SS and Arc sections, respectively. Applying this energy acceptance, lattice parameter in Table1 and assuming 1% coupling into Eq. (1), we get 24.7 hours Touschek lifetime for 0.5 mA bunch current (800 bunches for 400 mA in total).

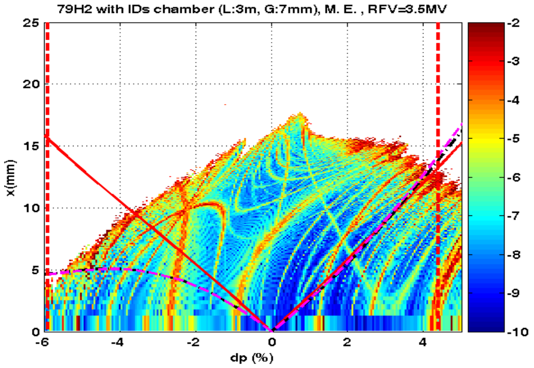

Figure 3: Induced amplitude at different location and off-energy frequency map tracking for the TPS lattice with RF voltage 3.5MV, one small gap chamber of 7 mm, multipole errors and 1% emittance coupling.

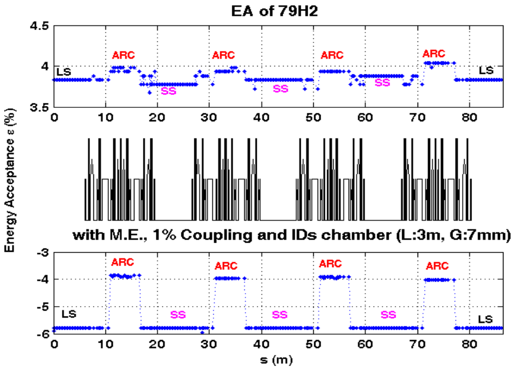

Figure 4: Upper and lower lines indicate the positive and negative EA of the lattice along one super-period. RF gap voltage is 3.5 MV, one small gap chamber of 7 mm, multipole errors and 1% emittance coupling.

OTHER TOUSCHEK LIFETIME ISSUES

Touschek Lifetime vs. Chromaticity

A large positive chromaticity can suppress beam instability. However, the dynamic aperture is reduced by higher chromaticity. Touschek lifetime as a function of RF gap voltage for different chromaticity settings is shown in Fig. 5.

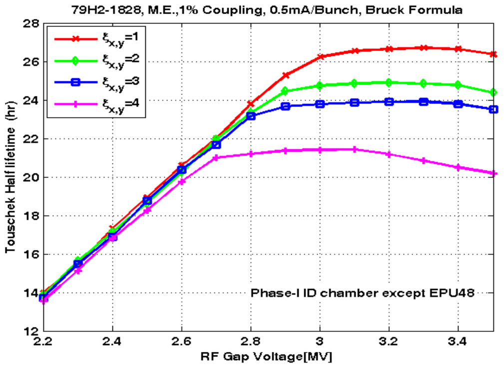

Figure 5: Touschek lifetime as a function of RF gap voltage for different chromaticity settings. Bunch current 0.5 mA, Phase-I IDs vertical chamber, multipole errors and 1% emittance coupling assumed in the simulations.

Touschek Lifetime vs. Coupling Ratio κ

In this lattice, there is no crossover of the fractional tunes in a range of energy deviation between -5.7% and 4%. EA is slightly reduced at positive energy due to the larger coupling ratio. The Touschek lifetime is dominated by bunch volume. Therefore, as shown in Fig. 6, the Touschek lifetime is proportional to square root of coupling ratio derived by Eq. (1).

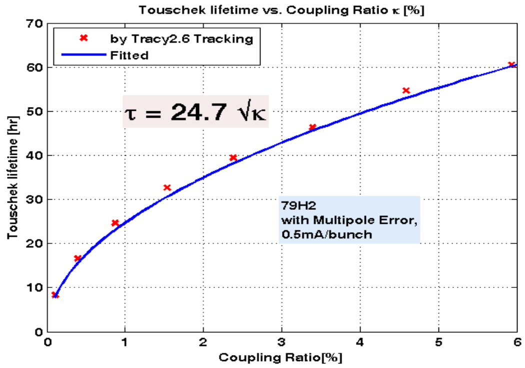

Figure 6: Touschek lifetime as a function of coupling ratio κ. RF gap voltage is 3.5 MV and multipole.

Touschek Lifetime vs. Vertical Acceptance

The vertical acceptance (VA) due to the narrow gap of IDs will decrease the Touschek lifetime. Fig. 7 is the Touschek lifetime as a function of VA with 0.5mA, 1% coupling, multipole errors and 3.1 MV RF gap voltage.

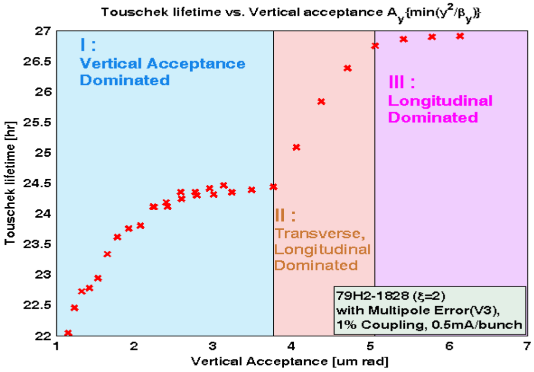

Figure 7: The Touschek lifetime as a function of VA.

The VA is reduced by an ID with gap from 7 mm to 5mm and length 1.5m to 5m at short straight section. The deformed RF bucket is (+4%, -5.3%) at 3.1MV gap voltage. The Touschek lifetime is dominated by VA for VA < 3.7um-rad, and then by transverse aperture and longitudinal bucket for 3.7 um-rad < VA < 5.1um-rad and finally by longitudinal bucket for VA > 5.1um-rad in I, II and III region, respectively.

Touschek Lifetime vs. Phase-I IDs

The corrected optics for ID effects was established [3]. Effects of IDs like beta-beat, tune shifts and phase advance are globally compensated by adjusting all 240 quadrupoles. After optics correction, EA of whole ring tracking is required. The EA of whole ring before and after optics correction for phase-I IDs except EPU48 are simulated and shown in Fig. 8. The Touschek lifetime before and after optics correction are listed in Table 3. We get longer Touschek lifetime after optics correction.

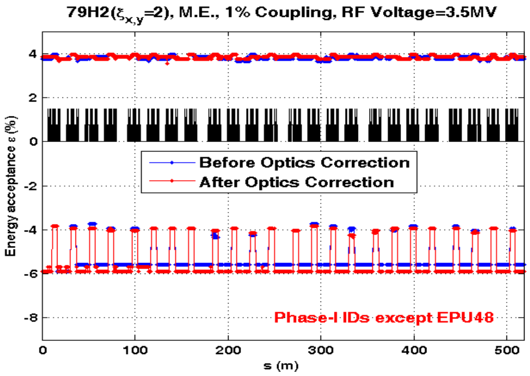

Figure 8: EA before and after optics correction for phase-I IDs except EPU48.

Table 3: The Touschek Lifetime Before and After Optics Correction for Phase-I IDs except EPU48

	Before Correction	**After Correction**
Vertical tune	**13.286**	**13.279**
Beta-Beat(x,y)	**0%, >1%**	**<0.5%, < 1%**
Touschek Lifetime (hr) (whole ring)	**25.73**	**26.57**
Touschek Lifetime (hr) (one super-period)	**24.73**	**25.65**

REFERENCES

[1] C.C. Kuo et al., "Lattice Study for Taiwan Photon Source", PAC'05, Tennessee, May 2005, p. 2989.

[2] M.S. Chiu et al., "Double Mini-Betay Optics of TPS Storage Ring", proceedings of IPAC'10.

[3] H. C. Chao et al., "Study of Insertion Device Modeling on TPS Project", proceedings of IPAC'10.