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Study of Touschek Lifetime in SSRF Storage Ring*

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Abstract Shanghai Synchrotron Radiation Facility (SSRF) is a 3rd generation synchrotron light source which is now under construction. The design emittance of the beam is 3.9nm·rad at the energy of 3.5GeV. Touschek lifetime is the dominant beam lifetime in SSRF for such a small beam emittance. The Touschek lifetime is the function of the energy acceptance of the storage ring. The energy acceptance is not only dependent on the RF voltage, but also restricted by the small physical or dynamic apertures, which makes the calculation complicated. In this paper the energy acceptances along the storage ring are calculated by the 6D tracking method based on the program Accelerator Toolbox (AT). Using those energy acceptance data, we can give a more close evaluation of the Touschek lifetime for different kind of conditions which we are interested in.

Key words SSRF, Touschek lifetime, energy acceptance, tracking

1 Introduction

The scattering of particles in a bunch of the storage ring may cause a change of momentum in transverse plane which will be transferred to a large energy divergence in longitudinal direction for relativistic particles. If the particle energy exceeds energy acceptance of the storage ring, the particle is lost and the lifetime is affected. This effect was firstly observed in the small storage ring ADA in 1963[1] and was explained by B. Touschek, so it is called Touschek lifetime which is a single scattering effect leading to the immediate loss of the scattering particles. Touschek lifetime is a serious problem for low energy storage rings; for high energy storage rings, the problem is relieved. However in the 3rd generation light sources, Touschek effect comes out to be a problem again. Because the particles in the bunches become quite dense, which greatly increases the events of the scattering; further more the physical aperture is reduced by insertion devices and the dynamic aperture is reduced by strong sextupoles, thus the off momentum particles will be more easily lost in transverse plane. In some cases, the effect of aperture on Touschek lifetime is more important than RF voltage and is difficult to deal with by using analytical method. So using the tracking method is a good choice.

A lot of theoretical investigations have been done since Touschek effect was discovered. The most popular formula was made by H.Bruck and J. Le Duff[2] as the bunch is considered as the 'ribbon beam', which is a proper assumption for bunches in electron storage rings and the result well matches the experiment when the energy acceptance is determined by RF voltage. Simulation work has also been done by A.Nadji[3] and M.Boge[4] to study Touschek lifetime in detail for Soleil and SLS storage ring recently.

2 Non-linear motion of the particles

The necessity of using the tracking method to investigate Touschek lifetime in SSRF lies on strong

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non-linear motion of the particles in the storage ring both in longitudinal and transverse directions.

For the longitudinal motion, the second order term of momentum compact factor α_2 plays an important role which can be defined in the following way:

$$\frac{\Delta l}{l_0}=\frac{\Delta C}{C_0}+\alpha_1\delta+\alpha_2\delta^2. \tag{1}$$

Where α_1 is the first order momentum compactor factor, $\Delta l/l_0$ is the total orbit lengthening factor, $\Delta C/C_0$ is the orbit lengthening factor caused by betatron oscillation. δ is the energy divergence. The formula indicates that the machine is more tolerant for negative energy divergence if α_2 is positive. From Fig. 1 we can find out that the energy acceptance is about 3.3% for the positive value and 4.0% for negative value when RF voltage is 4MV. A rough estimation gives α_2=2.7×10^{-3} which is 6.4 times of α_1 and is remarkable.

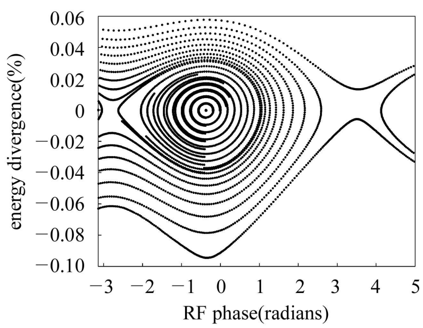

Fig. 1. Longitudinal phase diagram of SSRF storage ring($V_{\rm RF}$=4MV).

Strong sextupoles provoke nonlinearities which will distort transverse motions. Fig. 2 is the simulation results of the horizontal betatron motion at maximum dispersive place with sextupoles being turned on compared with setupoles being turned off.

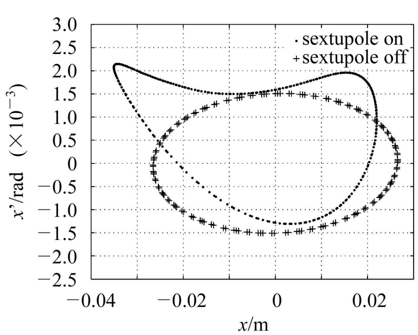

Fig. 2. Transverse phase diagram. At the place with maximum dispersion function.

The distortion increases the amplitude of the oscillation, then the particle will more easily get lost due to limited physical aperture.

Those non-linear motions are important for Touschek lifetime calculation and are hard to deal with by using analytical method. So we use tracking method to investigate those effects.

3 Transverse coupling effect

The coupling between horizontal and vertical motions can increase the vertical emittance which in turn increases Touschek lifetime by enlarging the bunch volume. But it also enhances vertical motion amplitude. When mini-gap chambers are employed, the off momentum particles may be scraped by the chambers, thus the Touschek lifetime will be pulled down.

The coupling coefficient κ used in this paper is defined in the following way:

$$\kappa=\frac{\sigma_y^2(s)/\beta_y(s)}{\sigma_x^2(s)/\beta_x(s)}. \tag{2}$$

Where $\sigma_{x,y}$ is the transverse RMS beam size. $\beta_{x,y}$ is the beta function.

The coupling factor is mainly from misalignment of quadrupoles and sextupoles. In most cases these coupling effects are small, but if the sum or the difference of the betatron tunes is an integer, it may drive a resonance oscillation which can greatly enhance the coupling. So a robust working point should be found out to avoid sum or difference resonance. The shifts of tunes of the two proposed SSRF lattices have been checked for different energy divergences when chromaticities were fixed at $[0,0]$. From Fig. 3 we confirm that the working points are safe for low order resonance. Yet the effect of coupling will be checked further below.

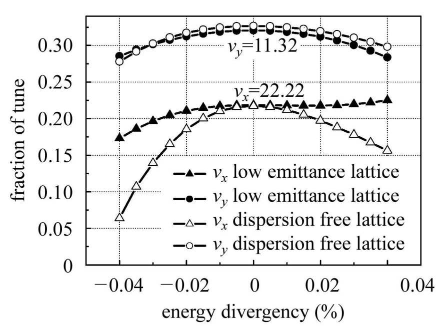

Fig. 3. Momentum-dependent tune variation.

4 Tracking method

One way to find out energy acceptance at a fixed place in the storage ring is to find out the particle with maximum energy divergence δ starting at the place with initial conditions $[x, x', y, y', \delta, s]$ which can circulate in the ring for sufficient turns.

(1) The initial conditions were set as $[5\times10^{-5}$, 0, 5×10^{-5}, 0, δ, $s]$. The particle is set with a little transverse displacement in order to start transverse motions. The step for searching the maximum δ is 0.1%.

(2) The physical apertures are defined for each element in the ring. If the coordinate of the particle is beyond physical apertures or energy divergence is much bigger than normal conditions (here we set the threshold for 7%), the particle is lost. Here dynamic aperture is ignored. The reason is if the particle is beyond dynamic aperture, the particle will eventually 'hit' on the physical aperture after certain turns. So the effect of dynamic aperture is integrated in the effect of physical apertures, which makes the calculation concisely.

(3) The number of turns for tracking is 500, which is equal to the turns of tracking for searching dynamic apertures in SSRF, and is about 4 times of synchrotron period. The number of turns is bigger than beating period N. The beating period N is determined by the full energy exchanging period between transverse directions caused by coupling effect[5].

$$N=\frac{2}{\sqrt{|\kappa|_q^2+\varDelta^2}}, \tag{3}$$

$$\kappa_q = \frac{1}{2\pi}\int_0^L \sqrt{\beta_x(s)\beta_y(s)}K(s)\times \exp\{\mathrm{i}[\varPsi_x(s)-\varPsi_y(s)-2\pi s\varDelta/L]\}\,\mathrm{d}s. \tag{4}$$

Where $\varDelta=\upsilon_x-\upsilon_y-q$, $\upsilon_{x,y}$ are betatron tunes, q is the integer part of $(\upsilon_x-\upsilon_y)$. $K(s)$ is the focusing strength of the skew quadrupoles, $\varPsi_{x,y}(s)$ is the betatron oscillation phase. From calculation N is about 9.

(4) There are two energy acceptances at a point in the ring: one positive, the other negative. The Touschek lifetime is calculated by using Bruck's formula[2]:

$$\frac{1}{\tau_{\mathrm{TL}}}=\frac{1}{2}\left[\frac{1}{\tau(\varepsilon^+_{\mathrm{Acc}})}+\frac{1}{\tau(\varepsilon^-_{\mathrm{Acc}})}\right], \tag{5}$$

$$\frac{1}{\tau}=\left(\frac{r_{\mathrm{e}}^2cN_{\mathrm{e}}}{8\pi\gamma^3\sigma_l}\right)\frac{1}{L}\sum_{n=1}^{M}\frac{C\left[\left(\dfrac{\varepsilon_{\mathrm{Acc}}(n)}{\gamma\sigma'_x(n)}\right)^2\right]}{\sigma_x(n)\sigma_y(n)\sigma'_x(n)\varepsilon^2_{\mathrm{Acc}}(n)}s(n), \tag{6}$$

$$\varepsilon_{\mathrm{Acc}}=\min\left[|\varepsilon_{\mathrm{rf}}|,|\varepsilon_{\mathrm{phy}}|,|\varepsilon_{\mathrm{dyn}}|\right]. \tag{7}$$

Where r_{e} is classical radius of electron, c is the velocity of light, N_{e} is the particle number in the bunch, γ is the normalized energy, $\sigma_l(n)$ is the RMS bunch length, $\sigma_{x'}(n)$ is the RMS value of x', L is the circumference of the ring, $s(n)$is the length of the n'th element in the ring, C is a function of energy acceptance and M is the number of elements in the ring. $\varepsilon_{\mathrm{rf}}$, $\varepsilon_{\mathrm{phy}}$, $\varepsilon_{\mathrm{dyn}}$ are the energy acceptance of RF voltage, the physical aperture and the dynamic aperture respectively and $\varepsilon_{\mathrm{Acc}}$ is the effective energy acceptance which is got from tracking method.

$\sigma_y(n)$ is calculated by Eq. (2). For lattice with quadrupole and setupole misalignment the κ can be calculated by AT using Ohmi's formula[6]. For lattice which has no misalignment, κ is assumed to be 1% globally.

(5) The closed orbit of the lattice has been corrected within 1mm deviation from design orbit in both vertical and horizontal plane.

5 Results and discussions

5.1 Calculation results of energy acceptance

One of the results of the energy acceptance along the ring calculated by the tracking method is shown in Fig. 4. From the figure we find out that the energy acceptance is very sensitive to the dispersion function. Where there's a bigger horizontal dispersion, there's a smaller energy acceptance. The reason is that if the particle with coordinate [0, 0, 0, 0, δ, φ] is scattered at non-dispersive place it will just follow a dispersive orbit through the ring, but when it is scattered at a dispersive place, it will generate an initial displacement due to dispersion and will oscillate around the dispersive orbit through the ring[4] making it more easily to get lost due to apertures.

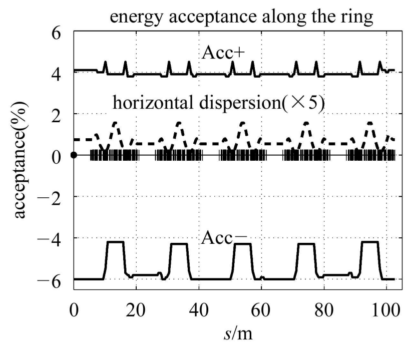

Fig. 4. Energy acceptance (%) along the quarter of the ring with $V_{\rm RF}$=6MV.

The negative energy acceptances are bigger than the positive ones, as has been analyzed in Section 1 which are caused by α_2.

5.2 Calculation results of Touschek lifetime

The Touschek lifetime of two modes of lattice has been calculated, one is the low emittance mode (mode Ⅰ) and the other is the dispersion almost free mode (mode Ⅱ). Their natural horizontal emittances are 3.9nm·rad and 7.9nm·rad respectively.

Touschek lifetimes of lattices without and with magnet misalignments have been calculated. In SSRF, the standard deviation σ of the quadupoles and sextupoles offsets misalignment value is 0.2mm, the roll misalignment value of qudrupoles is 0.2mrad.

The coupling coefficient of the lattice without misalignment is set to 1% globally in order to create vertical beam size. The lattices with misalignment of σ we used have the average coupling coefficient around 1%. The lattices with $2\times\sigma$ misalignment which have the average coupling coefficient around 2% have also been checked below.

The Touschek lifetime changes with RF voltage is shown in Fig. 5, where the chromaticity of the lattice is set to zero, the bunch length is 4.5mm, and the number of particles per bunch is 5.4×10^9.

From Fig. 5 we find out for all cases, the Touschek lifetime increases slowly when the RF voltage is above 4.5MV, which indicates that the dynamic aperture becomes the dominant effect on Touschek lifetime. Touschek lifetime of mode Ⅰ is bigger than mode Ⅱ (with misalignments) at high RF voltage region. The reason is maximum dispersion function of mode Ⅱ is bigger than that of mode Ⅰ. Big dispersion function may decrease energy acceptance at high RF voltage region for dynamic aperture turns up to affect energy acceptance which has been explained in Section 5.1. The dynamic aperture of lattice without misalignments is surely bigger than that with misalignments, so the effect of dynamic aperture turns up at even higher RF voltage which can be seen by the tendency of triangle lines in Fig. 5.

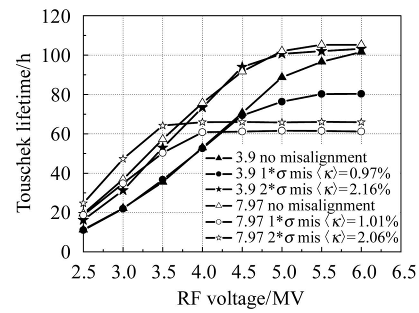

Fig. 5. Touschek lifetime changes with RF voltage.

The vertical chromaticity will be set around 6 in SSRF storage ring in order to suppress resistive-wall instabilitiy. Two sets of sextupoles are used to modulate chromaticities in the SSRF storage ring. The strong magnetic field may reduce dynamic aperture. Touschek lifetime will be decreased when dynamic aperture gets smaller. The effect of the vertical chromaticity is checked for two modes (with 1σ misalignment). The result is shown in Fig. 6, when ξ_y=6, the Touschek lifetime is greatly reduced. So setting the value of the chromaticity should compromise the needs of Touschek lifetime and transverse instability.

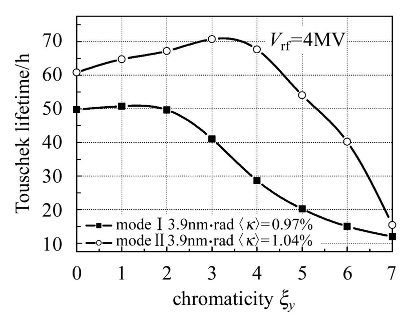

Fig. 6. Touschek lifetime changes with vertical chromaticity.

In the SSRF storage ring, in-vacuum insertion devises (IDs) will be employed. The effect of the mini-gap IDs was investigated by defining a part of vertical aperture at the place where IDs are installed to the value of the IDs gap size. The result is shown in Fig. 7. There's a sudden decrease of Touschek lifetime when reducing the gap size, which is a little different from the calculation results of other light sources[4]. Several other random misalignment seeds added to the lattice have been checked, no gradual decreasing of Touschek lifetime is found. From the data of energy acceptance, we find out that the energy acceptance at one place is changed from a small value to zero while the value at other places change a little. The vertical beta phase of the place is about $n\pi+\pi/2$ from IDs, n changes for different cases. Zero energy acceptance means that the bunch is thoroughly scraped by the IDs chamber.

The mini-gap chamber for SSRF is proposed to 3mm, it is very important to control the coupling coefficient to a small value.

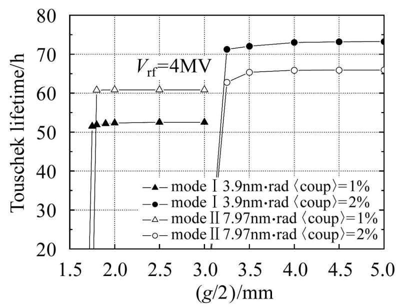

Fig. 7.　Effect of mini-gap IDs on Touschek lifetim.

The septum magnet in vacuum chamber may also scrape particles. Although the bumped orbit is closer to septum magnet, the duration is very short and the oscillation amplitude of the injected particle will soon be damped. So we just focus our calculation on normal operation conditions. We change the aperture in $-x$ (horizontal plane) direction at long straight section which represents the place of the septum magnet. The result is show in Fig. 8. The septum magnet is proposed set at $x=-18.5$mm at present. There seems to be no big problem to push it down to -16mm concerning Touschek lifetime.

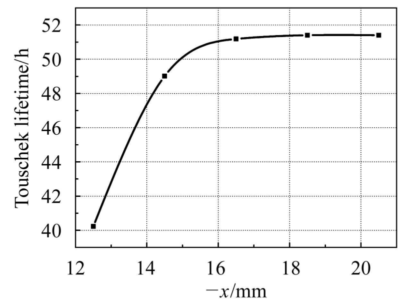

Fig. 8.　Effect of septum magnet on Touschek lifetime.

6　Conclusion

The 6D tracking method is used to investigate Touschek lifetime. The effect of dynamic aperture is integrated in the physical apertures, which makes the calculation concisely. Misalignments of magnets have been included in our calculation.

The results are reasonable, however they should be checked by measuring data in the future. The calculation results suggest that raising RF voltage above 4.5MV is inefficient for increasing the Touschek lifetime in SSRF. A 3rd harmonic RF cavity is now under consideration to lengthen the bunch to further increase the Touschek lifetime. High chromaticity needs strong sextupoles, which will reduce dynamic aperture, and thus decrease the Touschek lifetime. The value of chromaticity should compromise the needs of Touschek lifetime and transverse instability. The mini-gap IDs effect plays a crucial role for limiting the Touschek lifetime in SSRF, and the average coupling coefficient should be carefully controlled below 1%.

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References

1 Bernardini C et al. Phys. Rev. Lett., 1963, **10**: 407

2 Bruck H, Duff J L. Proc. 5th Int.Conf. High Energy Accelerators. Frascati, 1965. 284

3 Nadji A et al. Proceedings of PAC97, 1997. 1517—1519

4 Boge M et al. Proceedings of PAC99, 1999. 2430—2432

5 Tavares P F et al. Phy. Re. ST-A&B, 1998, **1**: 054001

6 Ohmi K et al. Phys. Rev., 1994, **E49**: 751

上海光源储存环束流托歇克寿命研究*

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摘要 上海同步辐射装置(SSRF)是目前在建的第3代专用同步辐射光源. 其储存环电子能量3.5GeV, 设计束团发射度3.9nm·rad. 托歇克寿命将是影响束流寿命的最主要因素, 它主要受限于储存环的能量接受度. 储存环的能量接受度不但取决于高频电压, 同时也受动力学孔径和物理孔径的影响. 因此能量接受度的计算将是复杂的. 通过计算机模拟跟踪的方法计算储存环各点的能量接受度, 其程序是建立在Accelerator Toolbox(AT)基础上的自编程序. 通过这些能量接受度数据给出更加准确的托歇克寿命, 并且分析了感兴趣的不同运行条件下的托歇克寿命的变化情况.

关键词 上海光源 托歇克寿命 能量接受度 模拟跟踪

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*上海光源工程资助

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