Experimental study using Touschek lifetime as machine status flag in SSRF *

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Abstract: The stabilities of the beam and machine have almost the highest priority in a modern light source. Although a lot of machine parameters could be used to represent the beam quality, there is no single parameter that could indicate the global information for the machine operators and accelerator physicists. For the last few years, a new parameter has been studied as a beam quality flag in the Shanghai Synchrotron Radiation Facility (SSRF). Calculations, simulations and detailed analysis of the real-time data from the storage ring have been made and the interesting results have confirmed its feasibility.

Key words: Touschek lifetime, beam quality, storage ring

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1 Introduction

Beam quality is of great importance for a light source that aims at providing stable synchrotron radiation for scientific research. A couple of machine parameters have been maturely used in most third generation storage rings around the world to indicate the beam status, such as the transverse beam size/emittance from a pinhole camera, the variance of the close orbit from the BPM system, etc. Other parameters, such as the beam length/energy spread from a streak camera, are also monitored in some facilities. However, monitoring a single parameter seems not enough to reflect the beam status while monitoring all of them simultaneously would eventually confuse the operators.

During the selection of the necessary parameters to be monitored, using the beam current to get some factor of the beam was believed to be a competitive economic proposal. Although the beam lifetime could interpret the beam status in some way, it is related to the beam charge so no convenient reference is available to say if the beam is in good status. Further processes are still needed to make this proposal a feasible solution.

1.1 Beam lifetime

A bunch containing N charged particles (electrons in most third-generation synchrotron radiation sources) in a storage ring decays due to a variety of mechanisms. Some of the non-trivial causes are: quantum lifetime (emission of synchrotron radiation), Coulomb scattering (elastic scattering on residual gas atoms), Bremsstrahlung (photon emission induced by residual gas atoms), and the Touschek effect (electron-electron scattering).

The charged particles are assumed to be electrons in this article unless otherwise noted.

The relative loss rate at a given time of the quantity of the beam defines the lifetime τ:

$$\frac{1}{\tau}\equiv-\frac{\dot{N}}{N}=-\frac{\dot{Q}}{Q}, \tag{1}$$

where $Q=-eN$ is the charge of the electron bunch.

The beam lifetimes due to the quantum character of synchrotron radiation, the Touschek effect, the elastic Coulomb scattering and the inelastic bremsstrahlung between the electron beam and the pure nitrogen gas are given by [1]

$$\tau_{\rm qu} = \frac{1}{2}\tau_w\frac{{\rm e}^{\xi}}{\xi}, \tag{2}$$

$$\frac{1}{\tau_{\rm tk}} = \frac{r_{\rm c}^2 cQ}{8\pi e\sigma_x\sigma_y\sigma_\ell}\frac{\lambda^3}{\gamma^2}D(\epsilon), \tag{3}$$

$$\tau_{\rm cs}(\text{hours}) = 10.25\frac{(cp)^2(\text{GeV}^2)\epsilon_{\rm A}(\text{mm}\cdot\text{mrad})}{\langle\beta(\text{m})\rangle P(\text{nTorr})}, \tag{4}$$

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and

$$\tau_{\rm bs}^{-1}(\text{hours}^{-1})=0.00653P(\text{nTorr})\ln\frac{1}{\delta_{\rm acc}}, \tag{5}$$

respectively, where $\tau_{\rm w}$ is the damping time, $\xi=\frac{A^2}{2\sigma^2}$ is a function of the acceptance of the beam A and the size of the beam bunch σ, $r_{\rm c}$ is the classical electron radius, $(\sigma_x, \sigma_y, \sigma_\ell)$ are the three dimensions of the bunch, $\lambda^{-1}=\Delta p/p_0|_{\rm rf}$ is the RF momentum acceptance of the ring, P is the pressure and $D(\epsilon)$ is the Touschek lifetime function, which is given by the following formula:

$$\begin{aligned} D(\epsilon) \;=\; & \sqrt{\epsilon}\left[-\frac{3}{2}\mathrm{e}^{-\epsilon}+\frac{\epsilon}{2}\int_\epsilon^\infty\frac{\ln u}{u}\mathrm{e}^{-u}\mathrm{d}u\right. \\ & \left.+\frac{1}{2}(3\epsilon-\epsilon\ln\epsilon+2)\int_\epsilon^\infty\frac{\mathrm{e}^{-u}}{u}\mathrm{d}u\right], \end{aligned} \tag{6}$$

where

$$\epsilon=\left(\frac{\beta_x\Delta p_{\rm rf}}{mc\gamma^2\sigma_x}\right)^2. \tag{7}$$

The total beam loss rate is the combination of all the beam loss rates listed above and can be written as:

$$\frac{1}{\tau}=\frac{1}{\tau_{\rm qu}}+\frac{1}{\tau_{\rm tk}}+\frac{1}{\tau_{\rm cs}}+\frac{1}{\tau_{\rm bs}}. \tag{8}$$

1.2 The Touschek lifetime

None of the components in the r.h.s. of (8) depends explicitly on the beam charge, except for the Touschek effect, which is based on Eqs. (2), (3), (4) and (5). The Touschek lifetime is of great importance and has already been simulated [2, 3] and measured [4–8] in many light sources. It is proportional to the beam charge, as shown in Eq. (3), so that the total beam loss rate can be simplified as the following equation if we use a "Touschek lifetime factor" k to represent the Touschek lifetime:

$$\frac{1}{\tau}=\frac{1}{\tau_0}+kQ, \tag{9}$$

where τ_0 is the combined quantum and vacuum lifetime

$$\frac{1}{\tau_0}=\frac{1}{\tau_{\rm qu}}+\frac{1}{\tau_{\rm cs}}+\frac{1}{\tau_{\rm bs}}, \tag{10}$$

and

$$k=\frac{r_{\rm c}^2c}{8\pi\mathrm{e}\sigma_x\sigma_y\sigma_\ell}\frac{\lambda^3}{\gamma^2}D(\epsilon), \tag{11}$$

so that

$$\tau_{\rm tk}=\frac{1}{kQ}. \tag{12}$$

For a quasi-steady state (e.g., the magnets, vacuum level, RF voltage, tunes and other machine parameters remain unchanged within a period of time, which is almost exclusive in many storage rings) the quantum lifetime, vacuum lifetime and the Touschek lifetime factor can all be considered as constants. A differential function about Q and t can be derived from Eqs. (1) and (9):

$$-\frac{\dot{Q}}{Q}=\frac{1}{\tau_0}+kQ. \tag{13}$$

Hence

$$\frac{1}{Q}=k\tau_0\left[\exp\left(\frac{t-t_0}{\tau_0}\right)-1\right], \tag{14}$$

where

$$t_0=\tau_0\ln\frac{k\tau_0Q(0)}{k\tau_0Q(0)+1} \tag{15}$$

is a constant of integration. Thus, a perfect machine would have an almost exponentially decreasing current curve.

As can be easily observed, the Touschek factor k is inversely proportional to the beam volume $\sigma_x\sigma_y\sigma_\ell$, the square of the beam energy, and the cube of the momentum acceptance. The slope of the function $D(\epsilon)$ is negligible in the field of small ϵ; that is, high energy when observing the deviate of the r.h.s. of Eq. (6). If $D(\epsilon)$ is regarded as a constant, then the relative Touschek factor can be easily determined by a simple form of the beam volume, beam energy and the RF acceptance.

2 Critical factors in the measurements

As a practical system, the beam diagnostic system could not totally remove the measurement errors. Besides, the physical variables mentioned above have hardly no disturbances. Although τ_0 and k are treated as invariants in (13), it may still be necessary to estimate the model's performance.

2.1 Impact of the quantum lifetime

The transverse acceptances are no less than 3 mm in the Shanghai Synchrotron Radiation Facility (SSRF), and the horizontal and vertical beam sizes are about 80 μm and 20 μm, respectively. The transverse damping time is 1.3 ms. The quantum lifetime in (2) could be regarded as long enough in SSRF because it is long enough in other third generation light sources. Hence, the fluctuation of the quantum lifetime could barely affect the total lifetime.

2.2 Influence of the pressure

The vacuum pressure that is detected is not constant during the operation and should not be ignored in a precision system. Eqs. (4) and (5) show that the beam loss rate of either Coulomb scattering or bremsstrahlung effect is directly proportional to the pressure. Thus, Eq. (9) should include the pressure related part to extract the Touschek lifetime:

$$\frac{1}{\tau}=\frac{1}{\tau_{\rm qu}}+mP+kQ. \tag{16}$$

Although the resolutions and accuracies of the vacuum gauges might not be satisfying in this situation, the reading of the gauge $P_1 = P + P_0 + n(P)$ would not be much trouble. The constant offset P_0 could be included in the quantum lifetime part, which is never paid attention to. The noise $n(P)$ can be decreased by curve fitting.

The pressure is affected by the radiation, so that it is beam charge related. But the heating is retarded and it is not the only factor that influences the degree of vacuum. Although the pressure and the charge might not be orthogonal to each other, they should be linearly independent.

2.3 Contribution of the beam size shift

The beam length σ_ℓ measurement would involve a streak camera, and neither the precision nor the update speed are satisfying at the moment, but the transverse sizes can be easily measured by using an X-ray pinhole camera. The non-linearities of the screen or the camera have already been calibrated carefully, so that we could use the transverse beam sizes as a comparison and an aid in our data analysis. The sizes that were calculated by using the original X-ray image of the radiation [9] and the point spread functions (PSF) [10] may have baseline offsets due to the measurement errors of the PSFs. This could have some effects to the Touschek lifetime fitting with the transverse sizes changing. We can expand the σ_i (i is x or y) terms in Taylor's series based on equation (3):

$$\frac{1}{\sigma_{0,\mathrm{i}}} = \frac{1}{\sigma_\mathrm{i}} \left(1 - \frac{\Delta_{\mathrm{PSF,i}}}{\sigma_\mathrm{i}^2}\right)^{-\frac{1}{2}} = \sum_{n=0}^{\infty} \frac{(2n)!}{(2^n n!)^2} \frac{\Delta^n_{\mathrm{PSF,i}}}{\sigma_\mathrm{i}^{2n+1}}, \qquad (17)$$

where $\sigma_{0,\mathrm{i}}$ is the actual beam size, σ_i is the calculated beam size by using the measured profile size $\sigma_{\gamma,\mathrm{i}}$, the calibrated PSF $\sigma_{\mathrm{PSF,i}}$ and the relation $\sigma_\mathrm{i}^2 = \sigma_{\gamma,\mathrm{i}}^2 - \sigma_{\mathrm{PSF,i}}^2$, $\Delta_{\mathrm{PSF,i}}$ is the difference between the square of the real PSF and the square of the measured one. The Touschek lifetime then can be expressed in the following form:

$$\frac{1}{\tau_{\mathrm{tk}}} = AQ \frac{1}{\sigma_x} \left(1 + \sum_k \frac{a_k}{\sigma_x^{2k}}\right) \frac{1}{\sigma_y} \left(1 + \sum_k \frac{b_k}{\sigma_y^{2k}}\right). \qquad (18)$$

If $\Delta_{\mathrm{PSF,i}}$ is relatively small then by comparing to σ_i^2, which is hopefully the truth, the higher order terms of the r.h.s. could be omitted.

3 Data analysis

The data are being recorded recursively without interfering with the operations of the machine as part of the global data warehouse system for a couple of years [11]. The analysis has been made before anything goes on-line.

3.1 Lifetime calculation

As much as we would like to use Eq. (14) to get the Touschek factor, there are still two obvious issues. First of all, Eq. (14) cannot be linearized, which will make the fitting a little complex. Nevertheless, the propagation of the fitting errors of other parameters would certainly affect the accuracy and resolution of the interested factor.

An algorithm based on the polynomial regression has been used to calculate the beam lifetime. A reasonable period n and a reasonable order k have been chosen in the following linear model:

$$I_{n\times 1} \simeq X_{n\times(k+1)} A_{(k+1)\times 1}, \qquad (19)$$

where I is the beam current vector, X the time matrix and A the coefficient vector: $I = (I_1, I_2, \cdots, I_n)^\mathrm{T}$, $A = (A_0, A_1, \cdots, A_k)^\mathrm{T}$ and

$$X = \begin{pmatrix} 1 & t_1 & \cdots & t_1^k \\ 1 & t_2 & \cdots & t_2^k \\ \vdots & \vdots & \ddots & \vdots \\ 1 & t_n & \cdots & t_n^k \end{pmatrix}.$$

Thus, the least-mean-square solution of the coefficient matrix is $A = (X^\mathrm{T} X)^{-1} X^\mathrm{T} I$, and the derivate would be

$$\dot{I}_{n\times 1} \simeq X^{(1)}_{n\times k} A^{(1)}_{k\times 1}, \qquad (20)$$

where $\dot{I} = (\dot{I}_1, \dot{I}_2, \cdots, \dot{I}_n)^\mathrm{T}$, $A^{(1)} = (A_1, A_2, \cdots, A_k)^\mathrm{T}$ and

$$X^{(1)} = \begin{pmatrix} 1 & t_1 & \cdots & t_1^{k-1} \\ 1 & t_2 & \cdots & t_2^{k-1} \\ \vdots & \vdots & \ddots & \vdots \\ 1 & t_n & \cdots & t_n^{k-1} \end{pmatrix} \cdot \mathrm{diag}(1,2,\cdots,k).$$

Therefore, the lifetime

$$\frac{1}{\tau} = -\frac{\dot{Q}}{Q} = -\frac{\dot{I}}{I} \qquad (21)$$

can be calculated by using the beam current data. A further weighted average process is needed to decrease the current noise and fitting errors by using overlapped intervals to estimate the lifetimes.

The calculated lifetime is actually the weighted averaged lifetime of the filled bunches. Since the bunches were evenly filled during the operations in SSRF, this averaged lifetime could be regarded as the lifetime of each bunch.

3.2 Vacuum lifetime estimate

The ingredient of the gas in the vacuum chamber is assumed to be invariant and the vacuum lifetime is inversely proportional to the pressure P. If the pressure varies while every other parameter related to the lifetime holds its own value, then the relation between the pressure and the corresponding vacuum lifetime with respect to the specific gas ingredient in SSRF can be easily calibrated. Fortunately, the pressure experienced a long significant change due to the destruction of the vacuum after an upgrade of the storage ring.

A series of data were carefully chosen to ensure that they share the same current and the same transverse size, which presumes that the Touschek lifetime was fixed and can be regarded as a constant. So, the total lifetime is linearly related to the pressure: $\tau^{-1}=AP+b$ where A and B are the coefficients to be determined (as shown in Fig. 1).

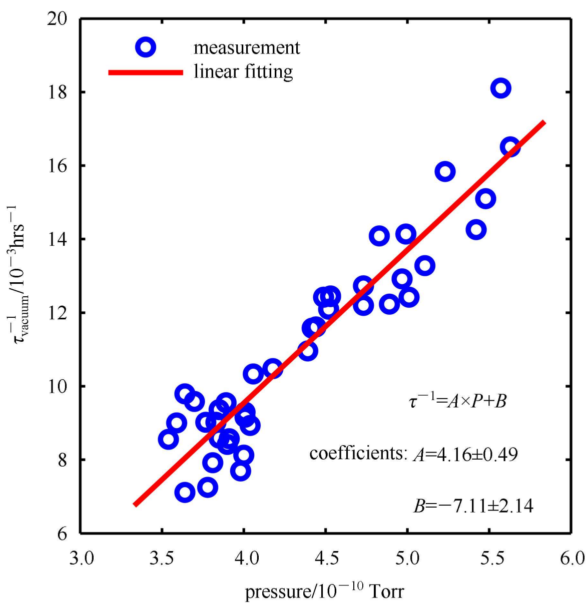

Fig. 1. An estimate of the practical form of the vacuum lifetime and the pressure. The data were tracked after a leakage of the storage ring during a hardware upgrade in 2012.

3.3 Touschek lifetime as a beam quality factor

Ignoring the quantum lifetime, the Touschek lifetime τ_{tk} would then be separated from the total lifetime by using the real time average pressure data P, which is provided by the vacuum gauges distributed around the storage ring, and the coefficient A in Fig. 1 to eliminate the vacuum lifetime part. The Touschek factor $k=1/Q\tau_{\text{tk}}$ would be calculated afterwards.

The transverse beam section, which was calculated in the X-ray pinhole image system, has been used as an aid to diagnose the ability of the Touschek factor. An illustration of the relation between the beam size and the Touschek factor is shown in Figs. 2 and 3. The results show that there is a strong linear correlation between the factor and the reciprocal of the beam size in a normal smooth operation period, as expected.

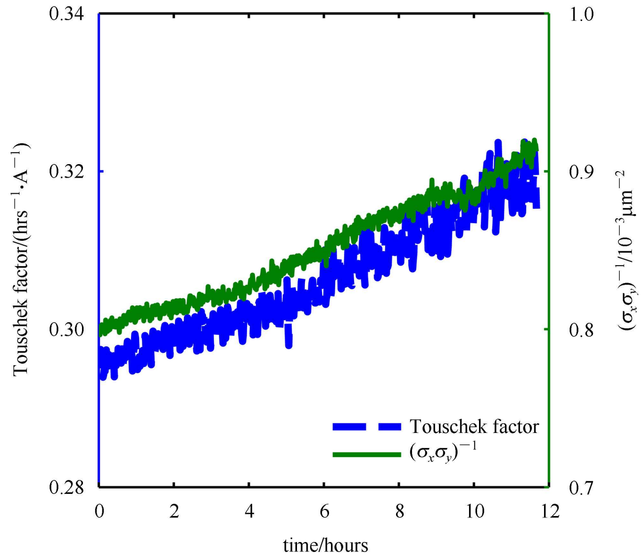

Fig. 2. A typical Touschek factor and beam size trend during a successful decay period. Data were acquired at Oct. 15.

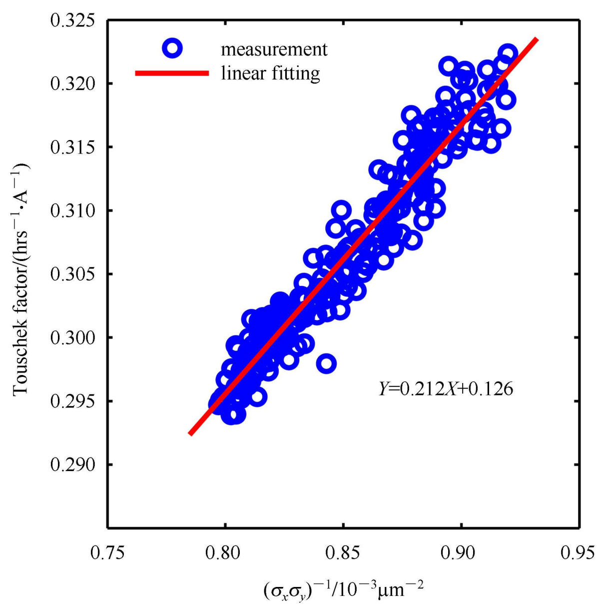

Fig. 3. The strong linear relation between the Touschek factor and the beam size.

A sudden change of the beam size, which always indicates a change of the lattice or other configuration of the machine, is not desirable during the operations and need extra attention. Fig. 4 demonstrates that the Touschek factor responded rapidly to the sudden change of the beam size.

Someone might have noticed that, in Fig. 4, although the trends of the beam size and the Touschek factor are similar, the relative change of the amplitudes and the slopes do have different information involved. This happens because the Touschek factor is a global parameter of the machine and is not affected by the beam size alone.

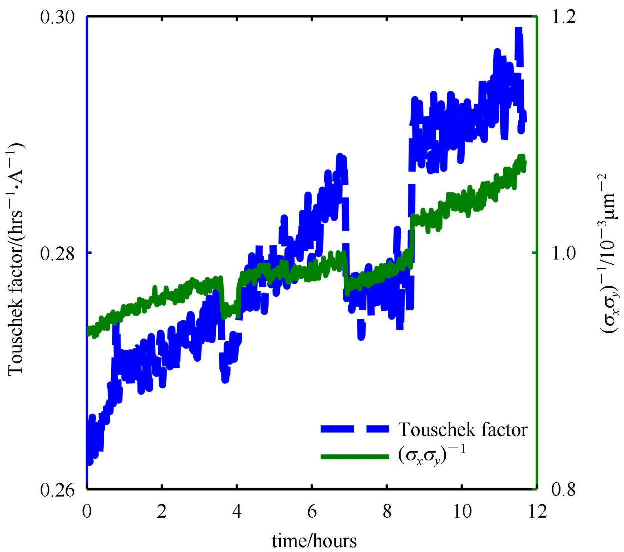

Fig. 4. Fast response to the sudden change of the beam size of the Touschek factor.

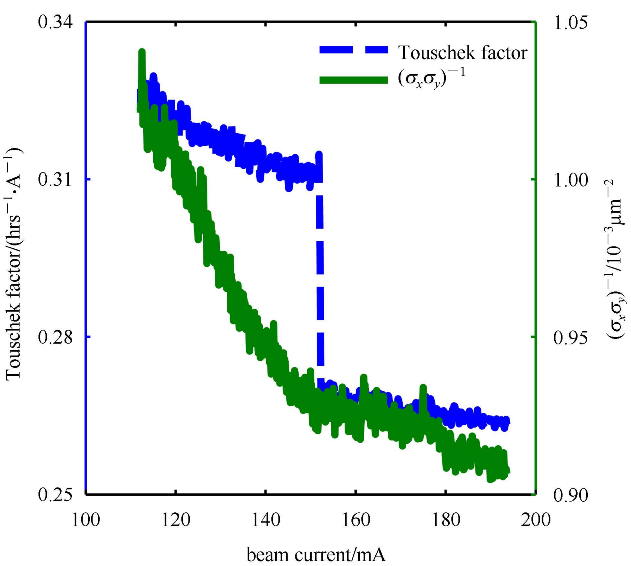

Fig. 5. Fast response of the Touschek factor to the sudden change of the machine status, while the beam size did not notice the difference. Data were acquired at Oct. 24.

Figures 5 and 6 give a more detailed illustration. Since it was in the decay mode, Fig. 5 should be viewed from right to left. Although there was a threshold at the beam current of 152 mA in the Touschek factor curve, the abnormality of the beam size was not quite visible without further analysis. The machine status was clearly divided into two different groups, as shown in Fig. 6.

This separation implies that the configuration could have been changed at the specific time or there was a hidden mechanism that introduced a new physical mode and the beam quality could deteriorate whenever the beam current was less than 152 mA. Two reasonable explanations had been made before further investigations: the change of the gap of an undulator, or the nonlinear effect of the machine.

If the Touschek factor has the ability to indicate the beam quality all by itself, then different beam statuses could be able to be separated and categorized. Fig. 7

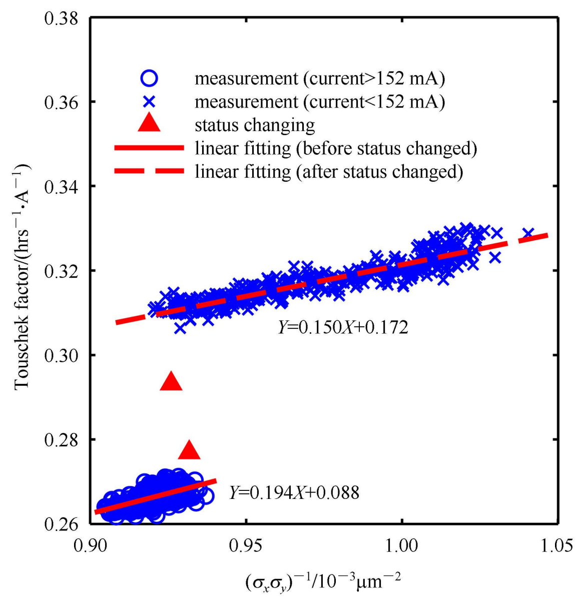

Fig. 6. The data are categorized into two group with the visible intermediate state.

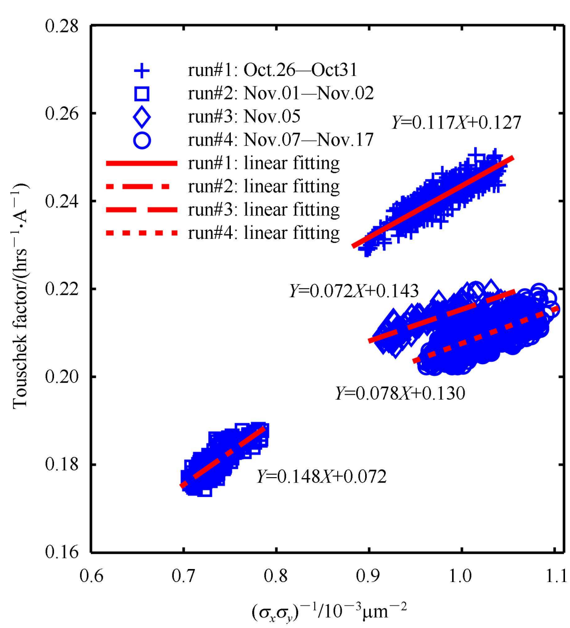

Fig. 7. Different operation period belongs to different groups with different beam/machine status.

shows another period of operations which was interrupted three times for various reasons. The beam status was believed to be stable during each successful piece. The beam size might be continuous and inseparable if we ignore the second piece. The Touschek factor, on the other hand, gave significant jumps between each piece, suggesting that these operations were not based on the same machine parameters.

The beam size change seen at the pinhole camera is local and should be cross checked with the β-function and the bunch length, which was quite stable during the operations, to confirm a change of emittance. However, the Touschek factor alone is able to diagnose the machine status. Since some of the machine parameters, such as the bunch length, dispersion functions and β functions, are difficult to be monitored on-line, this Touschek factor therefore is very important for the operators of accelerator physicists as a synthesized attribute of the machine and the beam.

4 Conclusions

In order to find a global flag that can be used to show an instant, hashed information of the beam and machine, a proposal based on the beam lifetime study was arranged. After an off-line analysis based on a series data from SSRF, the Touschek factor was confirmed to be sensitive to the beam sizes and other machine related parameters. It is also believed that this factor is able to reflect the change of the beam status fast enough.

The beam current data would be enough to calculate the Touschek factor so that it is very economic, simple, and intuitively clear. In addition, the algorithm is convergence and needs little intervention, so that it is feasible to provide the Touschek factor to the operators or physicists as an on-line flag of the beam/machine status. Long-term indication capability had also confirmed (as shown in Fig. 8 that the daily data of the Touschek factors during a typical period of operations, and the corresponding beam sizes and the Touschek factor, did not miss the changes of the beam size).

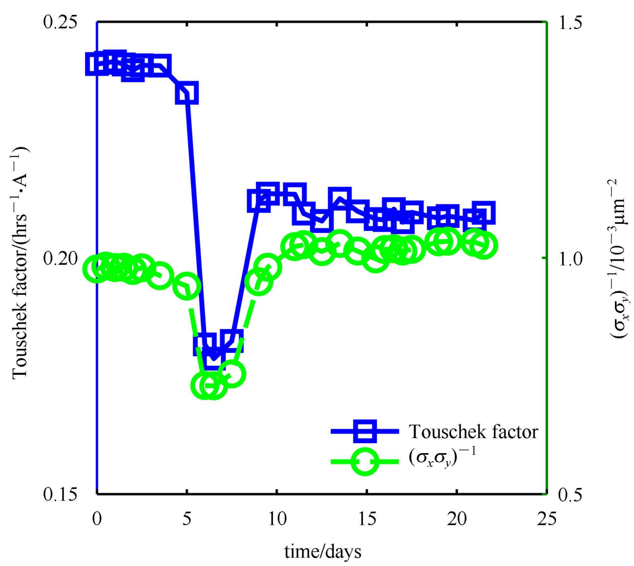

Fig. 8. Beam status tracking for long term operation.

During the experiments, the Touschek factor has shown some inspiring results in SSRF. Grouping the similar beam statuses could be useful for the operators when data were to be categorized before analysis. Finding the stepwise process of the transforming from one status to another could help the physicists during their beam experiments, such as looking for some critical parameters. Neither could be easily accomplished without the Touschek factor.

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