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# TOUSCHEK BEAM LOSS SIMULATION FOR LIGHT SOURCE STORAGE RINGS

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*Abstract*

In the low emittance storage ring, the beam loss is dominated by the Touschek effect. The knowledge of the beam loss is needed for protecting the machine, especially the insertion devices with a narrow gap, from the radiation damage by the scattered electrons. To this end, the manner of analyzing the loss distribution with respect to the various physical parameters is developed.

## INTRODUCTION

In light source storage rings, it is important to know the distribution of lost electrons due to the Touschek scattering for protecting insertion devices (IDs) from the radiation damage. This will become crucial especially in future light sources where in-vacuum IDs with a narrow gap are going to be used. While the Touschek scattered electron begins to oscillate in the horizontal direction with the amplitude proportional to the dispersion at the scattering point and to the momentum deviation after scattering, the motion is converted into the vertical direction due to the betatron coupling and some of the scattered electrons are lost at the narrow gaps of in-vacuum IDs. If the amount of beam loss at IDs is non-negligible, it will cause demagnetization of IDs and affect the beam performance and machien operation. We hence carried out computer simulations of Touschek beam loss and studied what is crucial for suppressing the beam loss at IDs by checking the effects of, e.g. the emittance $\epsilon$, beam energy $E$, dispersion $\eta$ at a Touschek scattering point, dimension of vacuum chamber.

We did simulations for two different types of light source storage rings in order to investigate the parameter dependence on Touschek beam loss: the present SPring-8 storage ring having a double-bend lattice structure with $E$ = 8 GeV, $\epsilon$ = 2.4 nm·rad and the circumference $C$ = 1436 m, and the planned SLiT-J storage ring [1] having a double double-bend lattice structure with $E$ = 3 GeV, $\epsilon$ = 1 nm·rad and $C$ = 350 m. At the arc, where the dispersion takes a maximum value, $\eta$ = 0.25 m in SPring-8 and $\eta$ = 0.18 m in SLiT-J, respectively. While the dispersion at ID straights is zero in SLiT-J, it takes a slightly non-zero value of 0.15 m in SPring-8 to reduce the emittance. Typical dimension of vacuum chamber is 70 mm × 40 mm (SPring-8) and 30 mm × 16 mm (SLiT-J). In addition to these, the effect of the beam scraper to protect the IDs form the radiation damage by the lost electrons was also studied. By comparing the simulation results the loss process is understood.

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## TOUSCHEK SCATTERING

The Touschek effect is the large angle Coulomb scattering of two electrons in a bunch. The transverse momentum of the betatron oscillation is converted to the longitudinal one and this leads to the beam loss if the momentum deviation is larger than the momentum acceptance limited by RF bucket or the induced betatron oscillation amplitude for off momentum electrons is beyond the transverse aperture.

### *Effects of Dispersion*

The central orbit for off momentum electrons is the dispersion[1] with the momentum deviation, so that the scattered electron starts to oscillate in horizontal direction with the amplitude proportional to dispersion and the momentum deviation. Though the scattered electron oscillates initially in the horizontal direction, the motion converts to the vertical due to the betatron coupling. Then the beam loss may occur at a narrow vertical aperture.

The horizontal displacement of the scattered electron is the sum of the dispersion and the oscillating amplitude which is proportional to the dispersion at scattering point. Then, in the case of scattering at smaller dispersion, the maximum momentum deviation below which the electron circulates a few turns without colliding with the horizontal aperture becomes larger. This means that the behavior of scattered electrons can differ for two cases: scattering at the dispersion-free or small dispersion straight section (SS) and at the arc with a large dispersion. In the former case the electrons circulate a longer distance and the beam loss rate at IDs in the vertical direction due to the coupling will be larger. On the other hand, in the latter case of scattering at the arc, the electrons will soon be lost by the horizontal aperture due to a large dispersion. The horizontal and vertical dimension of physical aperture (ID gaps and vacuum chamber) is hence closely related to the Touschek beam loss.

### *Momentum Distribution of Scattered Electrons*

The momentum deviation of the scattered electron is given by the Lorentz transform of the transverse momentum. Since the vertical emittance is so small compared to the horizontal, we only take account of the horizontal betatron oscillation in the transverse motion. Hence, the transverse momentum distribution is given by the Gaussian distribution with the rms value of $p\sigma_{x'}$, and the rms of momentum deviation of

[1] Here the dispersion means that including the derivative.

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the scattered electrons $\sigma_\delta$ is $\gamma\sigma_{x'}$, where we ignore the effect of the scattering angle as a zeroth order approximation.

The lower the emittance becomes, the smaller the momentum deviation $\sigma_\delta$ does. In other words, the amount of electrons of large momentum deviation decreases as the emittance is lowered, which leads to the reduction of the number of lost electrons. In practice, the collision rate is also proportional to the electron density in a bunch, so the loss rate grows as the emittance becomes small until the reduction of the momentum deviation overcomes the increase of the electron density. It is shown by simulations [2–4] that if the emittance reduces beyond some threshold value, the loss rate decreases and the beam lifetime becomes longer although such threshold values cannot be reached in the present third generation light source storage rings.

To study the effect of the beam scraper on the beam loss at IDs, we only need to know the relative change of the number of lost electrons and we calculate the loss distribution of the Touschek scattered electrons by using a simple Gaussian distribution for the momentum deviation with the rms value of $\sigma_\delta$. The beam extents in the horizontal and longitudinal directions are assumed to be negligible since they are quite small compared than that by the momentum deviation.

## APPROACH TO BEAM LOSS CONTROL

As explained above, the beam loss at the IDs are regulated by the dispersion, the physical apertures, and the linear and nonlinear coupling. The dispersion determines the horizontal displacement of the scattered electron according to a momentum deviation, and the coupling determines the magnitude of the vertical displacement. Hence the beam loss at the IDs is fixed according to the magnitude relationship between the horizontal and vertical displacements and the physical apertures.

To clarify the influence of these parameters on the beam loss, we calculated the turn-by-turn distributions of lost electrons in both horizontal and vertical directions. By surveying the correlation between these distributions and the initial momentum deviation of the scattered electrons, the loss process of the Touschek scattering can be examined in detail.

Among these distributions, the most suggestive one is the information on the turn number at the loss, since it directly represents the effect of the coupling. If the momentum deviation given by the Touschek scattering is over the acceptance limited by the RF bucket but still within the range that the electron does not collide with the horizontal aperture after passing one or more bending magnets, the scattered electron may survive over a few hundred turns, until it loses the energy by the radiation and collides with the horizontal inner aperture. In the meantime, when the coupling effect is strong, the vertical displacement grows and may hit the vertical aperture before restricted by the horizontal aperture.

The growth rate of the vertical oscillation depends on the dispersion and the momentum deviation as well as the coupling strength. For a large dispersion as the SPring-8 storage ring, the growth rate can become so fast as the vertical amplitude reaches the IDs only after 2 or 3 turns. It is difficult to protect the IDs from the scattered electrons by a scraper, since the electrons may pass through the scraper while the vertical amplitude is small even when the scraper gap is extremely closed compared to the IDs. Considering such a situation, the required number of scrapers and the installation location are examined.

In the case of SLiT-J, the scattered electrons circulate the ring with tens to hundreds of turns before being lost, which implies the effect of the coupling resonance and that the beam loss at IDs is well suppressed by a scraper. To clarify the dynamics of the coupling resonance, it is efficient to analyze the beam oscillation of the off momentum electron by means of the single particle tracking simulation. In the original SLiT-J lattice design, it was found that the normal sextupole coupling resonance is strongly excited due to an inadequate working point and this leads to the beam loss at IDs.

In this way, in discussing the Touschek beam loss and the protection of IDs from the damage, it is necessary to comprehensively understand the influence of dispersion, chamber size, resonance state and so on. By examining the loss distribution from such a viewpoint, it is possible to obtain information such as the necessity of a scraper, the effective installation position and the number, and so on. In the following, taking SPring-8 storage ring and SLiT-J as specific examples, the calculation results are shown from such a point of view to be considered.

## SIMULATION RESULTS

### *The SPring-8 Storage Ring*

The SPring-8 storage ring consists of 44 cells of modified double bend structure and 4 long (30 m) straight sections (LSSs), at one of which the 25 m long in-vacuum undulator (ID19) is installed. The vertical betatron function at ID19 is five times larger than that at normal undulators, so the minimum gap 12 mm of ID19 is effectively the narrowest vertical aperture in the ring. The next narrow vertical aperture is the vacuum chamber of the out-vacuum undulator ID07 installed at the other LSS, where the vertical inner radius is 15 mm. To protect a thin vacuum chamber at the injection section from the abort beam bombardment, the beam damper (BD) with a fixed horizontal aperture of 40 mm is installed. The emittance of the SPring-8 storage ring is 2.4 nm·rad, so the momentum deviation $\sigma_\delta$ of the electrons scattered at the arc section and at SS is 13.0 % and 13.5 %, respevtively. The momentum acceptance limited by the RF bucket is about 3 %.

To understand the beam loss mechanism in the SPring-8 storage ring, we calculated the beam loss distribution by the tracking simulation of the Touschek scattered electrons. A realistic ring model with finite betatron coupling and optics distortion was made by distributing normal and skew quadrupole error fields obtained by the response function analysis.

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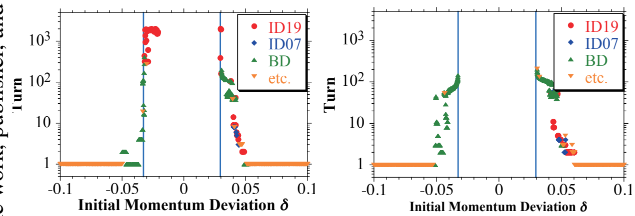

Figure 1: Turn number of loss for electrons scattered at arc (left) and SS (right) vs. momentum deviation for the SPring-8 storage ring.

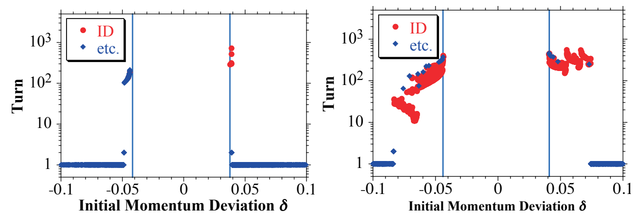

Figure 2: Turn number of loss for electrons scattered at arc (left) and SS (right) vs. momentum deviation for the SLiT-J.

Figure 1 shows the lost turn number at which of the scattered electron is lost as a function of the initial momentum deviation. For the negative momentum deviation in the case of scattering at the arc, there occurs beam loss at ID19 in the vertical direction even when the momentum deviation is within RF bucket. The local momentum acceptance at the arc is narrower than that at the SS since the vertical oscillation amplitude is so large as to reach the aperture due to the coupling of the large horizontal dispersion.

For the positive momentum deviation, the beam loss at IDs occurs in the range from 2 to several turns. In the SPring-8 storage ring the vertical beam scraper is installed at a normal straight section to protect the IDs from the radiation damage by the beam loss. However, as can be seen from these results, the beam loss at IDs occurs so fast after the scattering that it is difficult to completely suppress the loss at IDs reduce it by the scraper. In particular, for the scattering at the SS, even if the scraper gap is closed down to 2 mm, the beam loss at ID19 reduces only by half of that at 10mm (full open). This is because the electron with large momentum deviation circulates only a few turns after the scattering and it collides with not the narrowest gap of the scraper but ID19 due to the betatron phase relation.

### *SLiT-J*

The SLiT-J is the planned high brilliance light source storage ring of the middle energy 3 GeV with the natural emittance 1 nm·rad. It consists of 16 cells of double double bend achromat structure, and the circumference is 350 m. The momentum acceptance limited by the RF bucket is about 4 %. As in the SPring-8 storage ring, the in-vacuum undulators will be mainly used. Since the beam energy is lower than the SPring-8, the effects of radiation damage of the IDs will be severer.

In simulations the error kicks of skew quadrupole field are assumed to be at all 160 sextupole magnets. The distribution of the error field is random, and the strength is determined so as to give the emittance coupling 1 %. The horizontal and vertical betatron tunes of the original SLiT-J lattice are 29.17 and 9.23, respectively. Though the working point has been changed later to 28.17 and 9.23, we also used the old version of lattice in simulations for checking the effects of nearby resonances.

Figure 2 shows the turn number at the loss of scattered electron with respect to the initial momentum deviation. In the case of scattering at the arc, almost all electrons can not circulate the ring over one turn due to the narrow horizontal aperture. On the other hand, in the case of scattering at the SS, the range of the momentum deviation without colliding with horizontal aperture within one turn is about twice of that in the case of scattering at the arc. The scattered electrons with momentum deviation in this range circulate the ring over several tens or hundreds turns and in the meantime the vertical amplitude grows until the electrons lose at IDs. The growth of the vertical displacement is so slow, that the beam loss at IDs is almost removed by the scraper with gap 4 mm without considerably increasing the total beam loss.

To investigate the behavior of the electron scattered at the SS, the single particle tracking simulation for fixed momentum, *i.e.* without the radiation loss and the accelerating RF, is carried out. The simulation shows the amplitude of vertical oscillation blows up resonantly at momentum deviation $-6$ %, which leads to the beam loss of the Touschek scattering in SLiT-J. Nonlinear chromaticity implies that the normal sextupole resonance $\nu_x + 2\nu_y = 48$, which is the structure one, brings the beam blow up. By lowering the horizontal tune by 1, the resonance excitation is suppressed and the beam loss at the IDs can be removed.

## SUMMARY

For the purpose of protecting the IDs from the radiation damage by the Touschek scattering, the manner to investigate the beam loss of the scattered electrons in terms of the particle tracking simulation is developed. By analyzing the distribution of the lost electrons on the dynamical parameters, the beam loss mechanism is clarified. In addition, the situation of the coupling resonance is investigated by the single particle tracking simulation of the off momentum electron. According to thesee simulation results, the installation of the effective beam scraper is surveyed.

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