INJECTION BEAM LOSS AT THE SPRING-8 STORAGE RING

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Abstract

Capture efficiency of injected beam is extremely important for top-up operation because open photon shutter permits the bremsstrahlung from lost particles to be transported to experimental floor. Furthermore, since the SPring-8 storage ring has many in-vacuum insertion devices, the demagnetization by the lost electron bombardment is also a serious issue to the beam injection with gap closing. To clarify the loss mechanism of injected beam at the SPring-8 storage ring, we investigated the loss process under various conditions of the storage ring and measured the dependence of injected beam loss rate on gaps of insertion devices. Comparing the measurements with simulations, we found that an injected particle with a large horizontal amplitude begins to oscillate in vertical direction through error magnetic field and eventually disappears at the vertical limit. In this paper, we report the loss mechanism of the injected beam of the SPring-8 storage ring and the possible improvements of the capture efficiency.

INTRODUCTION

The SPring-8 storage ring is a high brilliance light source facility for x-ray experiments. Even at the SPring-8 storage ring with relatively high energy 8 GeV, the reduction in emittance may significantly shorten the beam lifetime due to the Touschek effect. In the several bunch operation with a high peak current per bunch the reduction of the lifetime becomes more conspicuous. To cure the short lifetime, we decided to operate the storage ring in top-up injection mode [1]. We also expect that the frequent beam injection keeping stored current constant stabilizes the thermal condition and in turn the stored beam orbit. The orbit stability of the stored beam is also an important factor for effective brilliance of light source ring.

Since many in-vacuum undulators are installed in the SPring-8 storage ring to produce intense synchrotron radiation for users, we should take care of beam loss at undulators in the top-up operation with gap closing. For this purpose we investigated the effects of the narrow gap of in-vacuum undulators on the injection beam loss. Since the beam enters the storage ring in horizontal plane, the injected beam has, in principle, no amplitude of vertical oscillation. Practically, owing to the coupling resonance by error field the horizontal oscillation flows into vertical direction. Hence the injected beam may be limited by the vertical aperture.

The major beam parameters for a typical low-emittance optics of the SPring-8 storage ring are listed in Table 1. Before the feedback system for transverse instabilities [2] has been installed, we adopted such large chromaticities in order to suppress instabilities. At present the chromaticities are decreased to 2 because the operation with low chromaticity is favorable for the capture efficiency as explained later.

energy [GeV]	8
horizontal / vertical betatron tune	40.15 / 18.35
horizontal / vertical chromaticity	8.0 / 8.3
natural emittance [nmrad]	3.4
emittance coupling ratio	0.002
energy spread	0.0011

Table 1: Parameters of the SPring-8 storage ring.

One of the characteristics of the SPring-8 storage ring is the existence of the magnet-free straight sections of 30-m long. The lattice functions of the SPring-8 storage ring including a long straight section is shown in Fig. 1. Note that the vertical betatron function takes a considerably large value in quadrupole magnets at both ends of the long straight section. It is expected that in the case of all in-vacuum undulator gaps open the vertical height of the vacuum vessel at the high vertical betatron function becomes the limit for injected beam.

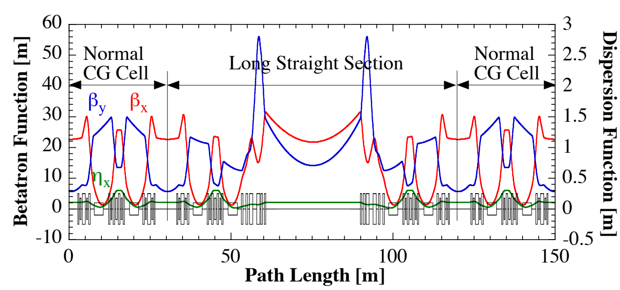

Figure 1: Lattice functions of low emittance optics of the Spring-8 storage ring. The red (blue) line denotes the horizontal (vertical) betatron function and the green one represents the horizontal dispersion function.

There are 26 IDs installed at the SPring-8 storage ring, 20 of which are in-vacuum undulators. The minimum gap of the in-vacuum undulators is 7 mm, which is much smaller than the vertical height 40 mm of vacuum chambers. The length of a standard undulator is 4.5 m. It is another characteristic of the SPring-8 storage ring that 25-m long in-vacuum undulator settles at one of four long straight sections. The betatron function at the long undulator is larger than that at the normal length undulator, so that

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the gap of the former is more severe for vertical limit than the latter.

EXPERIMENTS

At the SPring-8 storage ring the capture efficiency of injected beam can be measured by three ways. One is given by a ratio of the increment of the stored beam current to the transit current through beam transport from the booster synchrotron to the storage ring. The passing current is measured by the bunch charge monitor and the storage current by the DC current transformer (DCCT). This method is the easiest one to observe the injection efficiency, by which we monitor the efficiency during user operation. The others are defined by the decay rate of injected beam current observed by the turn-by-turn monitors. The turn-by-turn beam current is measured by the summation of readout voltage of the turn-by-turn beam position monitor or the integrated current transformer. Although, to know the absolute value of the beam current, one must calibrate the monitors, the capture efficiency is derived by the relative ratio between the current at the first turn and that after settling down. All these measurements of the capture efficiency coincide each other within a few %. Here, to clarify the loss process of the injected beam, our report concentrates on the measurement by the turn-by-turn current monitor.

In Fig. 2 we show the decay of injected beam current for various values of long undulator (ID19) gap. The injected

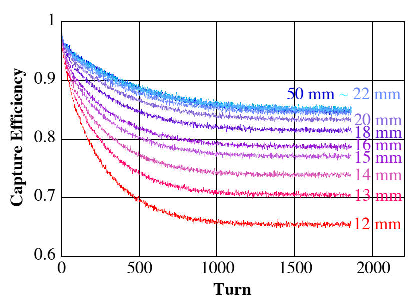

Figure 2: Current decay of injected beam for various values of a gap of ID19.

beam current exponentially decays, and the capture efficiency hardly changes from 50 mm gap to 22 mm. Under 20 mm, as the gap becomes small, the capture efficiency decreases. This result implies that the capture efficiency is limited by the vertical aperture.

For comparison we performed the similar measurements for normal length undulators ID20 and ID37. In Fig. 3 we show the capture efficiency as a function of an effective gap which is normalized by the square root of the vertical betatron function at the entrance or the exit of the undulator. The values of the vertical betatron function at the end of the undulator are indicated in Fig. 3. It is emphasized that the curves of capture efficiencies overlap each other.

Except for in-vacuum undulator gaps, the height of the vacuum vessel at the largest vertical betatron function of

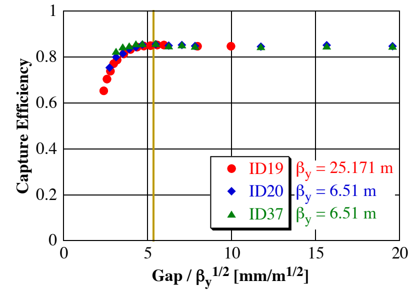

Figure 3: Capture efficiency as a function of an effective gap.

56 m limits the injected beam and the corresponding effective gap is 5.35 mm/m$^{1/2}$, which is indicated by the yellow vertical line in Fig. 3. When all the gaps of in-vacuum undulators open over the minimum effective height of the vacuum vessel, lost particles of injected beam collide with the chamber wall in the quadrupole magnets at either end of the long straight sections, where the vertical betatron function takes the largest value.

Since an injected beam decays exponentially, we can define its decay time. In Fig. 4 we plot the decay time as a function of an effective gap. One can find that in the region

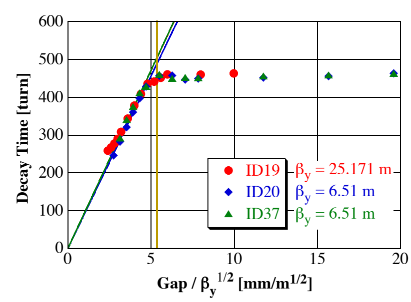

Figure 4: Decay time of injection beam current as a function of an effective gap.

under effective minimum height of the vacuum vessel the decay times are on a straight line starting from the origin. From this fact we expect that the tail of the particle distribution of injected beam in the vertical direction spreads approximately as inverse square of the distance from the beam center. This is explained as follows. Let y be the distance from the beam center and $\rho(y)$ the number of particles out of y. If the particle density at the tail y is proportional to the inverse square of y, we have

$$\rho(y) \propto \int_y^\infty dy y^{-2} = y^{-1}. \quad (1)$$

When the gap of in-vacuum undulator is y, the number of lost particles is given by $\rho(y)$. Provided that the diffusion process is sufficiently fast in contrast with the revolution, the decay time should be proportional to the inverse of $\rho(y)$ and hence to the vertical aperture y.

SIMULATIONS

In order to clarify the loss mechanism of the injected beam, we track injected particles by computer simulation. The particle tracking code developed at Spring-8 [3] is used for the simulation, which is based on 6×6 formalism and includes radiation loss and wake field. The ring model, i.e. the distribution of error magnetic field is obtained by the beam response analysis [4]. We track 1000 particles up to 1000 revolutions, and obtain the capture efficiency by the ratio of the number of particles at 1000-th turn to that at first turn. Physical apertures we considered are vacuum chamber wall, the gaps of in-vacuum undulators and the wall of the septum magnet.

In Fig.5 we show the simulation results of the decay of the injected beam current for various values of gap height of ID19. One can be convinced that the simulation well

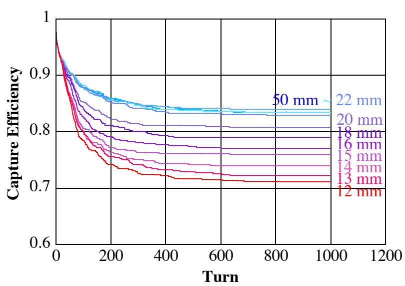

Figure 5: Calculated current decay of injected beam as a function of a gap of ID19.

reproduces the trend of the decay of injected beam current shown in Fig. 2.

By means of the tracking simulation, we prospect the loss points of injected beam. In Fig.6 we plot the distributions of lost particles over the circumference of the SPring-8 storage ring for the two cases of all gaps of in-vacuum undulators open and the gap of long undulator close o the minimum. As expected, in the former case, injected parti-

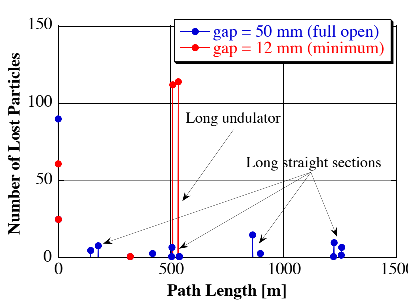

Figure 6: Number of lost particles over the circumference.

cles are lost at the septum wall and the vertical apertures at the quadrupole magnets of both ends of four long straight sections. On the other hand, in the latter case, injected electrons are lost at the entrance and the exit of the long undulator. The particles lost at the septum hit the wall within first several revolutions, while lost particles collide the vertical apertures after several tens revolutions.

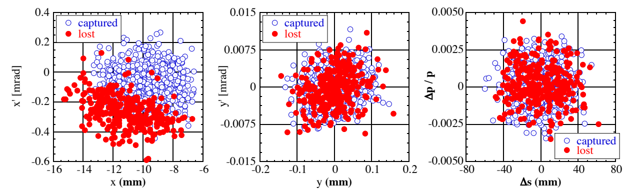

Figure 7: Lost particle distribution in the initial phase space.

In Fig. 7 we show the lost particle distribution in the initial phase space. Although in vertical and longitudinal plane lost particles evenly distribute, in horizontal phase space their distribution is localized. The particles, which are far from stored beam orbit in the horizontal direction and so have large amplitude, are liable to be lost.

DISCUSSIONS

Through the simulation we find that we can reduce the injected beam loss by decreasing the oscillating amplitude which is inevitable for off-axis injection. For this purpose the small emittance of the injected beam is effective. Hence we installed the slits at the beam transport line from the booster synchrotron to the storage ring [5] in order to cut the tail of the injected beam. As a bonus of the tail cut of the injected beam, we can make the injected beam trajectory closer to the stored beam orbit. This also contributes to the reduction of the injection beam loss.

The simulation reveals that the decrease of the chromaticities reduces the expansion of the vertical size of injected beam and hence improves the capture efficiency. Recently the feedback system suppressing the transverse instabilities is installed [2], so that we can stably operate the SPring-8 storage ring even with low chromaticities of (2, 2) and reduce the beam loss.

After all, we have accomplished the capture efficiency over 80 % even if all the gaps of in-vacuum undulator close to minimum. The simulation also implies that the resonance due to the error fields causes the expansion of the vertical size of the injected beam in spite of the small betatron coupling ratio of the SPring-8 storage ring. Then we plan to correct the skew quadrupole error fields further to improve the capture efficiency of the injected beam.

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