IMPACT OF NONLINEAR RESONANCES ON BEAM DYNAMICS AT THE SPring-8 STORAGE RING

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INTRODUCTION

For recent light source facilities of storage rings, the top-up operation is an extremely important item to demonstrate their thorough performance [1, 2]. In the top-up operation the beam is injected regularly to the ring during user experiment, so that the injection efficiency is expected to be as high as possible from the viewpoint of radiation safety and the demagnetization of the insertion devices.

Last year we have succeeded in fairly improving the injection efficiency of the SPring-8 storage ring. Before January 2010, we had operated the storage ring with the chromaticity $(\xi_x, \xi_y) = (2, 6)$. The vertical chromaticity had been set to a large value of 6 so as to suppress the beam instability in the beam filling mode with high current single bunches of 3 mA, while in the other beam filling modes the beam instability is well suppressed by the bunch-by-bunch feedback (BBF) [3]. Recently we improved the BBF by means of developing a bunch current sensitive attenuator [4]. With the help of this new BBF system, we could lower the vertical chromaticity ξ_y from 6 to 2. The lowering of the vertical chromaticity brought the injection efficiency improvement by about 10 %. In Fig. 1 we compare the injection efficiency in the user operation of 2009-5th and 6th cycles, whose average values are 85.2 % and 94.1 %, respectively. In the former cycle we operated the storage ring with $\xi_y = 6$ and in the latter with $\xi_y = 2$.

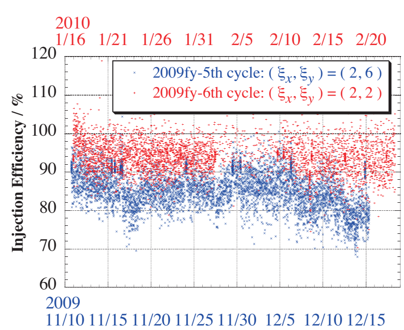

Figure 1: Injection efficiency in the user operation.

In order to elucidate the mechanism of the injection efficiency improvement, we study the beam dynamics of the stored beam with a large amplitude oscillation by means of turn-by-turn method. Analyzing the beam oscillation after kicked by a fast kicker, we observe the coupling resonance excitation. The causal relationship between the chromaticity and the injection efficiency is shed light on.

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INJECTION BEAM LOSS PROCESS AT THE SPring-8 STORAGE RING

The SPring-8 storage ring is a high brilliance light source for hard x-ray experiments. The basic optics structure consists of the modified double bend lattice, whose dispersion function at a straight section is not zero for the purpose of reducing the natural emittance. One of the characteristics of the 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. 2.

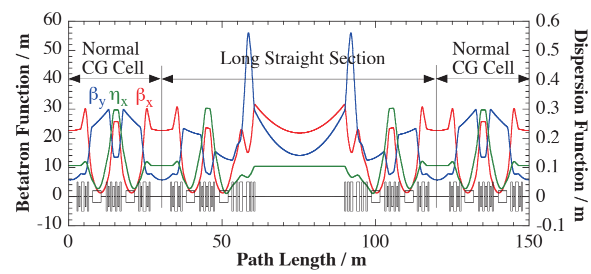

Figure 2: Lattice functions of low emittance optics of the Spring-8 storage ring. The red (blue) line denotes the horizontal (vertical) betatron function and the green one represents the horizontal dispersion function.

The relevant parameters of the SPring-8 storage ring are listed in Table 1. The vertical chromaticity was changed from 6 to 2 on January 2010 as mentioned avobe.

Table 1: Parameters of the SPring-8 Storage Ring

Beam energy [GeV]	8
Horizontal / vertical betatron tune	40.14 / 18.35
Horizontal / vertical chromaticity	2 / (6 $\longrightarrow$) 2
Natural emittance [nmrad]	3.4
Emittance coupling ratio	0.002
Energy spread	0.0011
Revolution period [μs]	4.8

There are installed many insertion devices at the SPring-8 storage ring, most of which are in-vacuum type. It is observed that the injection efficiency of the storage ring drops as gaps of these in-vacuum ID's close [5]. Although there is the effect of the magnetic field of the ID's on the beam dynamics, the narrow vertical aperture of closing the ID gap is the principal cause of the injection efficiency decrease.

In order to investigate the injection beam loss process, we installed the beam scraper in the vertical direction. Figure 3 shows the dependence of the injection efficiency on the scraper gap. In Fig. 3 the abscissa denotes the half gap of the scraper normalized by the square root of the vertical betatron function. The narrower the scraper gap becomes, the lower the injection efficiency drops. This implies that the injected beam primarily oscillating in horizontal direction is also spread vertically and lost by the vertical aperture. Namely, the coupling resonances enhance the vertical oscillation of the injected beam, which leads to the beam loss.

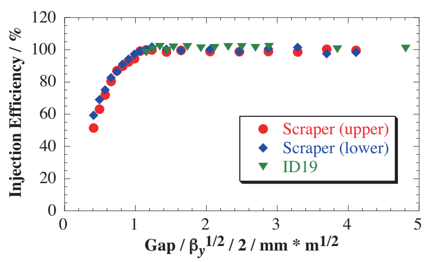

Figure 3: Injection Efficiency vs. scraper gap.

At one of the long straight section the 25-m long in-vacuum undulator, ID19, is installed, whose minimum gap is 12 mm, the narrowest normalized vertical aperture along a circumference of the SPring-8 storage ring. The injection efficiency with the ID19 gap closing is also shown in Fig. 3, which agrees with those with the scraper gap. Note that the starting points of injection efficiency dropping, as the gaps of the scraper and ID19 closed, agree with each other. This fact also means that the injection efficiency is affected by the transverse dynamics, or the coupling resonance.

COUPLING RESONANCE ANALYSIS

In order to investigate the coupling resonance excitation, we measure the stored beam oscillation kicked by a fast kicker in terms of the turn-by-turn beam position monitor (BPM) [6]. As the fast kicker we use the injection bump magnet system, which consists of four pulse magnets forming the bump trajectory for the stored beam. By exciting the bump magnets by upstream or downstream half, we can instantly give the initial horizontal amplitude in either the positive or negative direction to the stored beam. We extract the information of the coupling resonance excitation from the Fourier analysis of the beam oscillation.

Effect of Chromaticity

For the purpose of investigating the change of the resonance excitation, we measure the stored beam oscillation kicked by the bump magnets while changing the height. Figure 4 shows the beam oscillation in time domain measured by the turn-by-turn BPM for the cases of chromaticity $(\xi_x, \xi_y) = (2, 2)$ (left) and $(2, 6)$ (right), where the figures at the upper line describe the horizontal oscillation and the ones at the lower do the vertical.

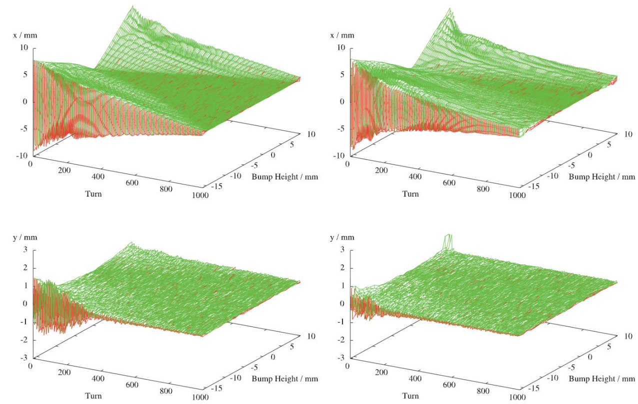

Figure 4: Beam oscillation in time domain after kicked by pulse bump magnets.

We show the result of the Fourier analysis of the beam oscillation in Fig. 5 in the order as same as in Fig. 4. In Fig. 5 we find many higher order coupling modes excited as well as the fundamental betatron tunes. Furthermore, it is found that the larger the vertical chromaticity is, the larger the amplitude dependent tune shift grows, which is confirmed by the simulation as in Fig. 6.

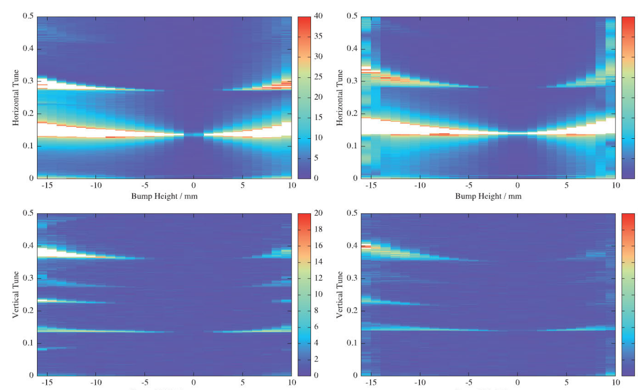

Figure 5: Fourier transform of beam oscillation after kicked by pulse bump magnets.

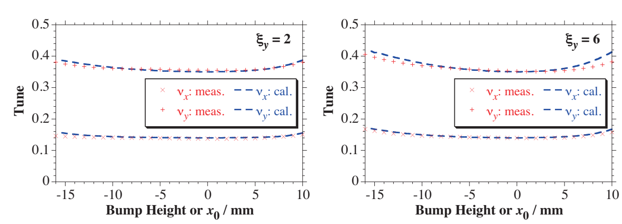

Figure 6: Comparison of the measured amplitude dependent tune shift with the simulation.

The second higher harmonics $2\nu_x$ of horizontal betatron tune clearly appears in the horizontal oscillation, which is excited by the normal sextupole magnet field. On the other hand, the second order modes, $2\nu_x$, $-\nu_x + \nu_y$, and $1 - \nu_x - \nu_y$, are observed in the vertical oscillation, in addition to the linear coupling mode ν_x. Here the modes of $-\nu_x + \nu_y$ and $1 - \nu_x - \nu_y$ are excited by the normal sextupole magnetic field, and the mode of $2\nu_x$ by the skew sextupole one.

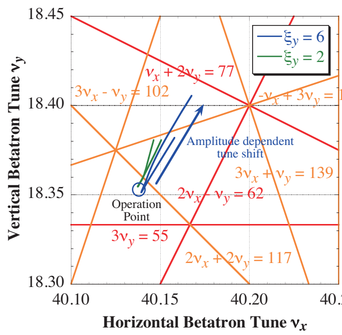

Figure 7: Tune excursion of the betatron tune with the growing amplitude in the tune map.

Figure 7 shows the footprint in the tune map for the beam with a large oscillation amplitude in the horizontal direction. The resonance lines of the third and fourth order are also drawn, and some of these resonances, in particular the third order ones, were found to have an impact on the beam dynamics.

As well known, the betatron tune suffers an amplitude dependent tune shift due to the effect of the sextupole magnet field. The tune shift in the case of the vertical chromaticity ξ_y = 6 is larger than that of ξ_y = 2 as shown in Fig. 6. Hence in the case of ξ_y = 6 the tune of the oscillating beam with the large amplitude like the injected beam approaches to the third order resonance $\nu_x + 2\nu_y = 77$ closer than in the case of ξ_y = 2. The resonance enhances the coupling of horizontal and vertical oscillations, and hence the beam becomes to oscillate in the vertical direction larger. As a result, the electron whose vertical oscillation amplitude has grown large collides with the aperture and will be lost. Thus the injection efficiency is improved by lowering the chromaticity to prevent the betatron tune from approaching the harmful resonances.

Effect of Betatron Tune

Through the study of the beam dynamics of the beam with a large amplitude, we are aware of the importance of the operation point. For example, though the nominal operation point of the SPring-8 storage ring is set to $(\nu_x, \nu_y) = (40.15, 18.35)$, it is observed that the injection efficiency at (40.14, 18.35) is several percent higher than that at the former. This is explained as follows.

Figure 8 shows the power spectrum of the stored beam oscillation kicked horizontally by the injection bump magnets. In the present example of Fig. 8, the mode of $2\nu_x$ in the vertical oscillation, which is excited by the skew sextupole magnet field, is excited larger at the operation point (40.15, 18.35) than that at the nominal operation point. This is because the second harmonics $2\nu_x$ at the nominal operation point gets closer to the vertical tune than at (40.14, 18.35). In other words, the operation point approaches the coupling resonance excited by the skew sextupole magnet field. Hence the vertical oscillation for ν_x = 40.15 becomes larger than that for ν_x = 40.14, and the injection efficiency of the former gets worse than the latter. By carefully choosing the operation point to keep it away from harmful resonance lines of the third and the fourth order, we have realized the high injection efficiency, being from 93 % to 95 % constantly in the user operation period.

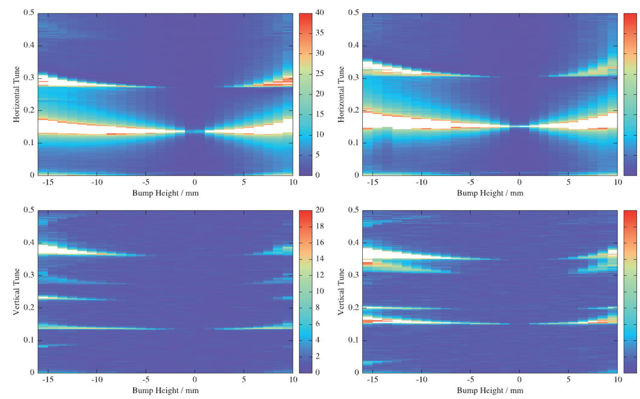

Figure 8: Fourier transforms of beam oscillation of operation point (40.14, 18.35) (left) and (40.15, 18.35) (right). Figures at upper (lower) line represent the horizontal (vertical) oscillation.

SUMMARY

At the SPring-8 storage ring, some of the higher order coupling resonances reduce the injection efficiency. It is found that we can restore the reduction by preventing the betatron tunes of the injected beam from approaching to the coupling resonances by means of lowering the chromaticity and carefully choosing the operation point.

When users change the gap of insertion devices, the betatron tunes change by the quadrupole magnetic field component of the magnet arrays and in some cases the operation point moves toward the harmful resonance lines. To prevent lowering of the injection efficiency by this effect during user operation, we plan to add auxiliary power supplies to nearby quadrupole magnets for the purpose of keeping the betatron tunes constant.

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