Beam Performance

Developments and Upgrades of Storage Ring and Booster Synchrotron

Improvement of the injection efficiency into storage ring

For recent light source facilities of the storage ring, the top-up operation is extremely important for demonstrating their thorough performance [1,2]. In the top-up operation, the beam is injected regularly to the ring during users experiment and the injection efficiency is expected to be as high as possible from the viewpoint of radiation safety and the demagnetization of insertion devices. Last year, we succeeded in improving the injection efficiency substantially and we report on it here.

Before January 2010, we operated the storage ring with the chromaticity (ξ_x, ξ_y) = (2,6). The vertical chromaticity was set to a large value of 6 so as to suppress the beam instability in the filling mode with high current single bunches of 3 mA. Recently, we have improved the bunch-by-bunch feedback (BBF) system for suppressing instability by developing a current sensitive attenuator [3]. With 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 efficiencies in the user operations of the 2009: 5th and 6th cycles, whose averages are 85.2% and 94.1%, respectively.

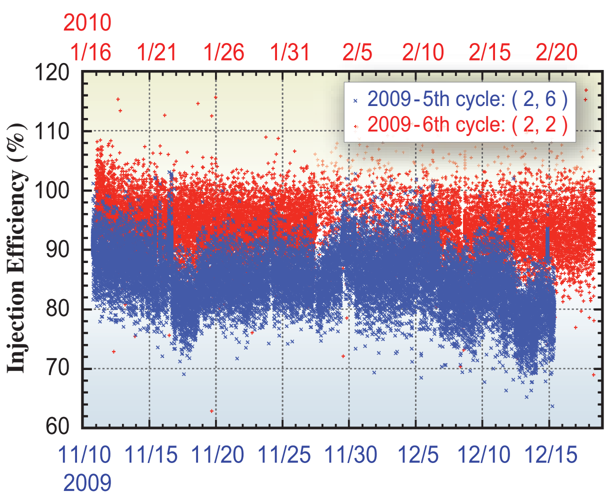

Fig. 1. Injection efficiency in user operation.

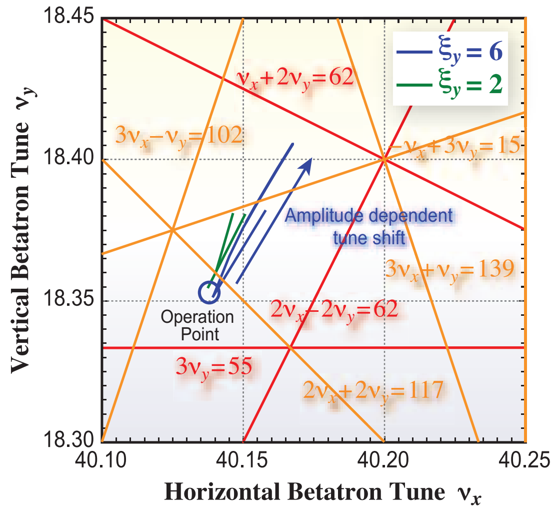

Fig. 2. Tune excursion of the beam with growing amplitude.

In the former cycle, we operated the storage ring with $\xi_y = 6$ and in the latter cycle with $\xi_y = 2$.

To elucidate the mechanism of the injection efficiency improvement, we studied the beam dynamics of electrons with large-amplitude oscillation [4]. Figure 2 shows the betatron tune excursion in the tune map for electrons with large-amplitude oscillation in the horizontal direction. The resonance lines of the third and fourth orders are also drawn, and some of these resonances, particularly the third-order ones, were found to have an impact on beam dynamics. As is well known, the betatron tune suffers an amplitude dependent tune shift due to the effect of the sextupole magnet field. This tune shift at the vertical chromaticity $\xi_y = 6$ is larger than $\xi_y = 2$. Hence, at $\xi_y = 6$, the tune of the oscillating beam with a large amplitude like that of the injected beam approaches the third-order resonance $\nu_x + 2\nu_y = 62$, closer than at $\xi_y = 2$. The resonance enhances the coupling of horizontal and vertical oscillations, and hence the beam becomes to oscillate in the vertical direction more strongly. As a result, the electron whose vertical oscillation amplitude has become large collides with the aperture and is lost. Thus, the injection efficiency is improved by lowering the chromaticity to prevent the betatron tune from approaching harmful resonances.

Through the study of the beam dynamics with large amplitude, we are aware of the importance of the operation point. For example, although the nominal operation point of the SPring-8 storage ring is set to (ν_x, ν_y) = (40.15, 18.35), it is observed that the injection efficiency at (40.14, 18.35) is several percent higher than that in the former. This is explained as follows. Figure 3 shows the power spectrum of the vertical oscillations of the stored beam kicked horizontally by the injection bump magnets. By exciting two of the four pulsed bump magnets, we can give some amplitude to the stored beam. The analysis of the beam oscillation gives information on the coupling resonance excitation. In the present example in Fig. 3, the mode of $2\nu_x$, which is excited by the skew sextupole magnet field, is excited larger at the operation point (40.15, 18.35). This is because the second harmonics $2\nu_x$ at the nominal operation point gets closer to the vertical tune than that 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 becomes lower than the latter.

By carefully choosing the operation point to keep it away from harmful resonance lines of the third and fourth orders, we have realized a high injection efficiency, from 93% to 95%, constantly in the user operation period. When users change the gap of the insertion devices, the betatron tunes change with the quadrupole field component of their magnetic field and in some cases the operation point moves toward harmful resonance lines. To prevent the decrease in injection efficiency by this effect during user operation, we plan to add auxiliary power supplies to nearby quadrupole magnets to keep the betatron tunes constant.

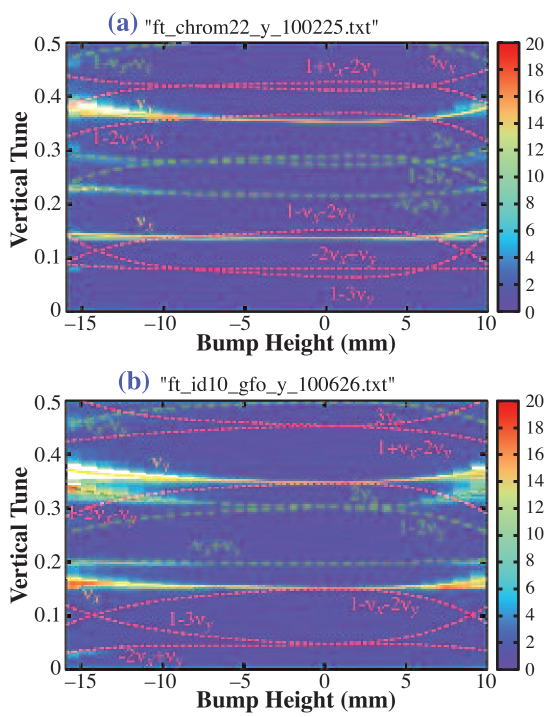

Fig. 3. Spectra of vertical beam oscillations for ν_x = 40.14 (left) and 40.15 (right) when kicked by pulsed bump magnets.

Beam-based alignment for injection bump magnets of storage ring using remote tilt-control system

In the top-up operation mode, it is important to suppress the oscillation of the stored beam during beam injection. During the injection, four pulsed magnets (bump magnets, BP1 ~ BP4) are excited by four individual power supplies to generate a bump orbit. If a magnet has alignment error in rotation around the beam axis (tilt), the stored beam is oscillated in the vertical direction. In addition, even if the rotational alignment error is negligible, the beam out of the median plane is kicked in the vertical direction. Also, there is a small long-term drift of the vertical beam positions in the bump magnets, which causes the gradual increase in the extent of oscillation. Therefore, it is necessary to realign the bump magnets periodically.

We have already developed a remote tilt-control system to achieve a smooth realignment [5]. To measure vertical oscillation, the beam was stored in only one rf bucket and was shaken by the pulse of the bumps without beam injection. The beam position was measured turn-by-turn using the strip-line type beam position monitor for the bunch-by-bunch feedback system [6]. The monitor has the highest position resolution of all the position monitors in the storage ring. To obtain responses to the tilts of each magnet, the oscillations were measured under the condition that the magnets were tilted intentionally. Tilt errors were calculated by the least-squares method using the responses.

An example of the oscillation before the correction is shown in Fig. 4 (dashed line). After the correction, amplitude was suppressed to 1/25 (solid line). However, the amplitude could not be made zero or below the noise level. The residual oscillation could be attributed to the horizontal oscillation observed in the vertical axis in the position monitor coordinates. A small angle mismatch between the observation and oscillation axes introduces a false observation, because the horizontal oscillation has an amplitude

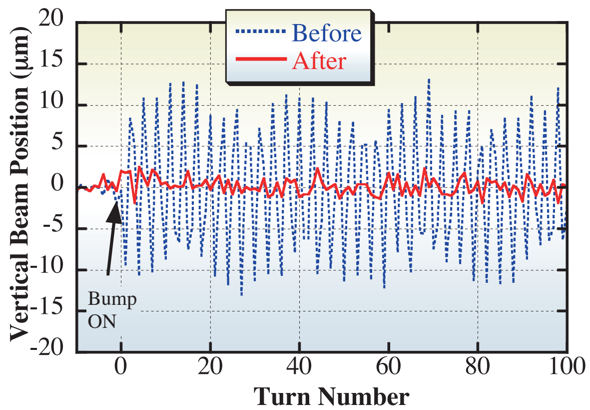

Fig. 4. Vertical beam position *versus* turn number. Dashed and solid lines indicate the positions before the correction and after the correction, respectively.

two orders of magnitude larger than the vertical one.

To confirm the source of the residual oscillation, frequency analysis was carried out by the FFT method using the position data from the 1st turn to the 128th turn. The peak amplitude *versus* frequency is shown in Fig. 5. The horizontal component could be separated from the vertical component because their frequencies agreed with the fractional tunes in the horizontal and vertical directions. Before the correction (dashed line), the vertical component was 20 times as large as the horizontal one. After the correction (solid line), the peak amplitude of the vertical component was suppressed to 0.41 µm and was smaller than that of the horizontal component. In addition, the amplitude of the horizontal oscillation remained unchanged, which meant that the observed residual oscillation came from the horizontal one.

We succeeded in suppressing the vertical oscillation due to the bump magnets to the submicron order, a value less than one tenth of the beam size.

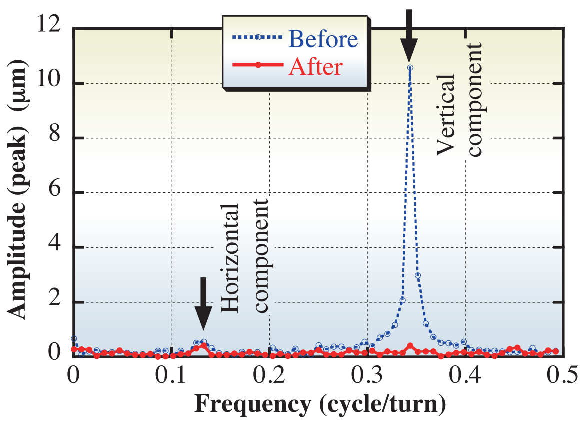

Fig. 5. Peak amplitude *versus* frequency. Dashed and solid lines indicate the amplitudes before and after the correction, respectively.

Development of bunch-by-bunch feedback system

The hybrid filling composed of high bunch current singlet bunches and low bunch current bunch trains are requested by users [3]. For this filling, the bunch-by-bunch feedback system (BBF) has to simultaneously stabilize the mode-coupling beam instabilities of the singlets and the multi-bunch instabilities of the trains, in both horizontal and vertical directions. However, the signal level from the beam position monitor (BPM) for the BBF is also proportional to bunch current; therefore, the signal level from the high bunch current singlets is two orders higher than that from the trains, and the BBF saturates for singlets. To compensate for such a bunch current dependence of the BPM signal level, the old bunch current sensitive bunch-by-bunch automatic attenuator, the attenuation range of which was 10 dB, was upgraded to a new one with a range of 40 dB [7]. The controller based on the SPring-8 BBF signal processor was developed to measure the bunch current and drive the digital and analog attenuators, as shown in Figs. 6 and 7, respectively. Also, the large feedback kick necessary to suppress the strong single-bunch instability under the large horizontal oscillation excited by the formation of the bump orbit was achieved by upgrading the kicker to a high-efficiency horizontal kicker.

With these upgrade of the BBF, we achieved the top-up operation with the filling of a singlet with 6 mA/bunch and trains with 900 bunches with 0.1 mA/bunch, under the worst-user operation condition for the instability with almost all the in-vacuum insertion devices closed to their minimum gap.

Further increase in the bunch current of the singlet to 10 mA/bunch and an increase in the freedom of the range of filling for the train are intended for use with a

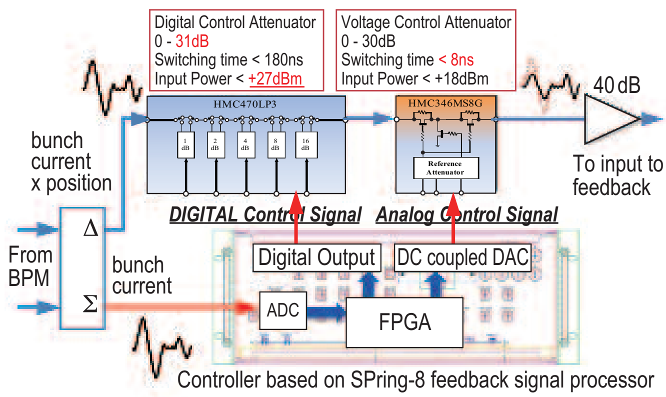

Fig. 6. Upgraded bunch current sensitive automatic attenuator.

new high-efficiency kicker under manufacture. The freedom of the range of filling will also be achieved by the operation of the fast correction kicker [8] developed by the vacuum and magnet team to reduce the oscillation amplitude excited by bump orbit formation.

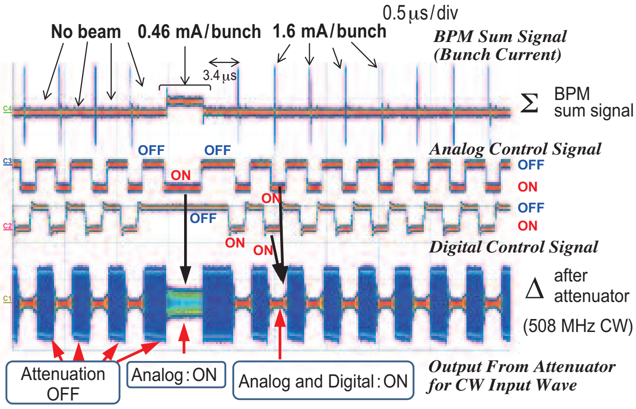

Fig. 7. Bench test result with the BPM sum signal of stored beam with 1/14 + 12 bunch filling.

Development of accelerator diagnostics beamlines

At diagnostics beamline II (BL05SS), we constructed and commissioned the transport line of the monochromatic X-ray beam from optics hutch II to the experimental hutch. The first light was successfully delivered to the experimental hutch in April 2010. We have developed a γ-ray stopper made of tungsten heavy alloy for the transport line and have installed it downstream of the double-crystal monochromator of optics hutch II. The γ-ray stopper consists of a rectangular parallelepiped block of heavy alloy with a rectangular through-hole (Fig. 8). The heavy alloy block serves as both a shield of high-energy radiation accompanying the incident white X-ray beam to the monochromator and a vacuum pipe transporting the monochromatic X-ray. It is equipped with two conversion flanges at both ends through metallic O-rings and is connected to neighboring vacuum chambers of the beamline with conflat flanges with an outer diameter of 70 mm (ICF70). The heavy alloy block as well as its sealing with metallic O-rings is leak-tight and the measured helium leak rate was less than 10^{-11} Pa·m^3/sec. The γ-ray stopper was baked at 200°C after installation in the beamline, reaching a pressure of 10^{-7} Pa in the UHV.

A fast turn-by-turn diagnostics system of the transverse emittance and the energy spread of the electron beam is being developed in the experimental hutch of diagnostics beamline II. It is based on the measurement of the angular divergence of the higher harmonics of the ID. The vertical divergence of the ID photon beam is sensitive to the energy spread of the electron beam because of the small vertical emittance of SPring-8, whereas the horizontal divergence is dominated by the horizontal emittance. The sensitivity of energy spread measurement has been studied experimentally by observing the 19th harmonics of the ID [9]. The fast diagnostics system consists of a fast fluorescent screen, an image intensifier and a fast-gated CCD camera. It is expected to be useful for tuning the injection of the high-quality beam to be delivered from the C-band linac for XFEL. Test of the fast diagnostics system is in progress by observing the injection beam from the booster synchrotron and simultaneously measuring the longitudinal bunch length with a visible streak camera (VSC) at diagnostics beamline I (BL38B2). Figure 9 shows an example of the results of the turn-by-turn bunch length measurement. The VSC operated in the dual-time base mode, which has a fast vertical scan for measuring the bunch length and a slow horizontal scan for resolving each turn after injection. Although the bunch length of the injection beam is longer than that of the stored beam in equilibrium, the energy spread of the injection beam is comparable with the stored beam. Therefore the bunch length after injection decreases in the one-quarter period of the synchrotron oscillation and then increases in the next one-quarter period. Such features of the bunch length of the injection beam have been successfully observed by the VSC.

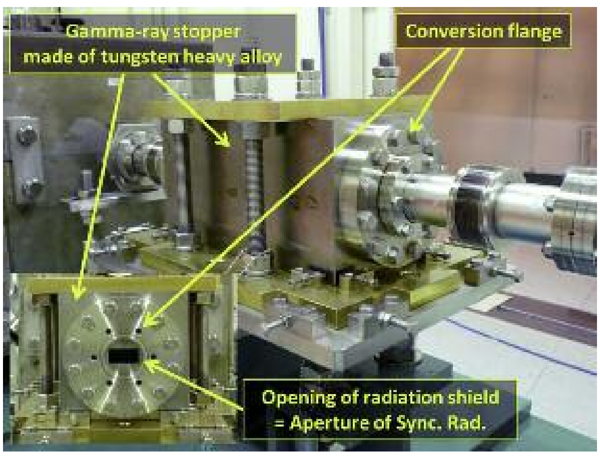

Fig. 8. γ-ray stopper made of tungsten heavy alloy developed for transport line of monochromatic X-ray beam of diagnostics beamline II.

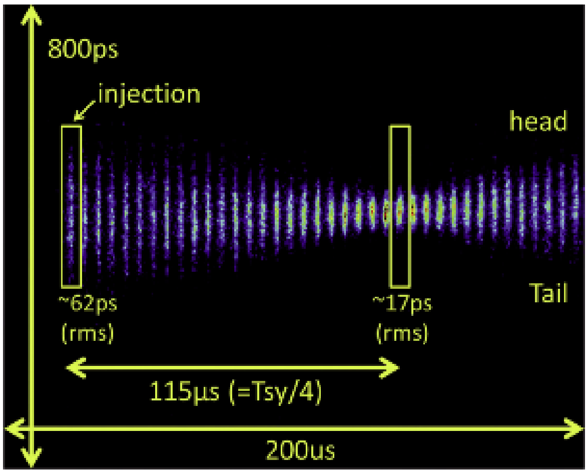

Fig. 9. Example of the results of turn-by-turn bunch length measurement of injection beam from booster synchrotron by VSC at diagnostics beamline I.

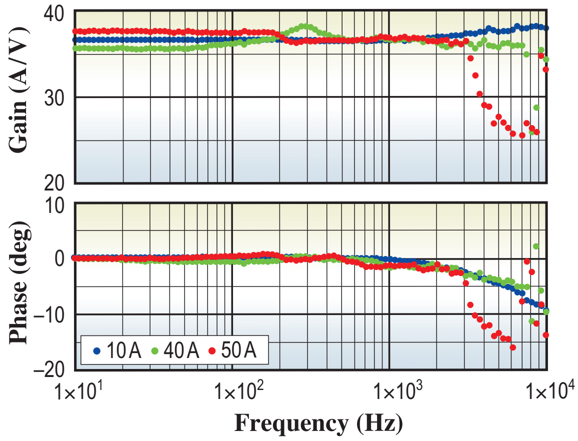

Fig. 10. Measured frequency responses of power supply.

Research and development of femtosecond pulse X-ray generation

An X-ray with an energy of 10.7 keV and a pulse width of 600 fs in two standard deviations can be generated with a short-pulse generator using superconducting crab cavities in one of the long straight sections of the storage ring. A phase stability within 14 mdeg among the crab cavities is required to realize this scheme [10]. We developed a 300 kW phase shifter to stabilize the phase fluctuation and found that its performance could satisfy this requirement [11]. In this report, we describe a power supply developed as a driver of this phase shifter, which is an inductive load of 50 μH/40 mΩ.

The power supply consists of DC power supplies whose voltages are powers of 2, such as 4 V, 8 V ... and 256 V, and power MOSFET switches. Its driving frequency range is from DC to 10 kHz with a current of 50 A and a voltage of 550 V. We measured the frequency response of the power supply in an offline test using a load with the same impedance as that of the phase shifter. Preliminary results for driving currents of 10 A, 40 A and 50 A are shown in Fig. 10. Although several improvements in the stability and reliability are needed for the power supply, tests on the important parameters have already been completed.

Developments and Upgrades of Linac

Development of RF isolator for vacuum waveguide system

Although the RF waveguide systems for the regular section of the linac are evacuated by ion pumps, the waveguide system for the injector section, which is equipped with circulators, is filled with a pressurized SF_6 gas because a vacuum-type circulator has not yet been developed.

An RF phase of a microwave propagated in such a pressurized waveguide varies along with fluctuations in its insulation gas pressure, the atmospheric pressure and its body temperature. This RF phase variations result in non-negligible beam instability. Now, we are planning to update the SF_6 waveguide system to a vacuum-type one to improve its RF phase stability and renew its aged components. As SF_6 is a type of global greenhouse gas, its usage should also be reduced. We thus started an R&D of vacuum-type circulators and isolators.

Since the outgassing rate from garnet ferrites used in a circulator was expected to be very large, we measured it at an estimated operation temperature of 100°C. It was found that the outgassing rate is only about 34 times larger than that of typical stainless steel and is acceptable for evacuation by ion pumps.