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Energy Feedback System for the PLS-II Linac

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The upgraded Pohang-Light-Source (PLS-II) was opened to the public in 2012. Among many improvements of the PLS-II, a top-up operation was one of the highlights of them, and the stability of the electron beam was improved significantly. For the top-up operation, a stable injection from the linac to the storage ring was critically important, so that an energy feedback system was introduced to reduce the energy jitter of the linac electron beam. The result of the feedback system was successful and the measured energy jitter was less than ±0.1% (rms). In this work, the details of the energy feedback system are presented. It includes the setup for the energy feedback system, measurement results in the optimization process, and the future work for a better performance.

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I. INTRODUCTION

The upgrade of the Pohang Light Source (PLS-II) was finished at the end of 2011 and it was opened to the public again in March 2012. After the upgrade, the beam energy was increased from 2.5 GeV to 3.0 GeV, and the beam current was increased from 200 mA to 400 mA. The emittance was improved from 18.9 nm rad to 5.8 nm rad, and the number of straight sections for insertion devices were doubled from 12 to 24. To increase energy and the current of the electron beam, the radio frequency (RF) system in the storage ring was upgraded to enhance the RF power, and three superconducting RF cavities were installed [1].

In addition to the hardware upgrades, the operation mode of the storage ring was changed. In the PLS, the beam current decayed from the maximum current of 200 mA to the minimum current of 100 mA and electron beams were injected 2 or 3 times in a day. The thermal expansion of the vacuum chamber reached its maximum just after the injection and slowly came back to the previous position as the beam current decay. This means that the electron beam drift can be generated during the operation. In the PLS-II, on the contrary, the top-up mode operation is being used, and the electron beam is injected in every 3-minute to keep the 400 mA beam current [2].

For the top-up mode operation, a beam loss should be minimized during the injection because it can make unwanted radiation near the beam loss point. The number of the injection is increased from 3 times to 480 times in a day for the top-up mode operation, and a minimized beam loss during the injection is an important issue for the radiation safety. In addition, if there is a beam loss during the injection, then the duration time of the injection can be increased. This is not a good condition for the beamline experiment because beamlines can be suffering from the beam fluctuation during the injection.

For the minimum beam loss during the injection, the electron beam parameters from the linear accelerator (linac) should be kept as stable as possible. Among several parameters of the electron beam, the energy stability was critically important, so that the energy feedback system was introduced to the PLS-II. After the installation, the energy feedback system removed the energy drift successfully and became an essential element of the top-up operation.

II. PLS-II INJECTION AND ENERGY FEEDBACK

The PLS-II consists of a full energy linac (3 GeV), a beam transport line (BTL), and a storage ring. Because of the angle and the level differences between the linac and the storage ring, the BTL has three horizontal and three vertical bending magnets, in addition to the quadrupole and the corrector magnets as shown in Fig. 1. At the end of the BTL, there is a Lambertson-type septum magnet for the electron beam injection to the storage ring. The distance from the electron beam center to the septum wall is only 2 mm to the horizon-

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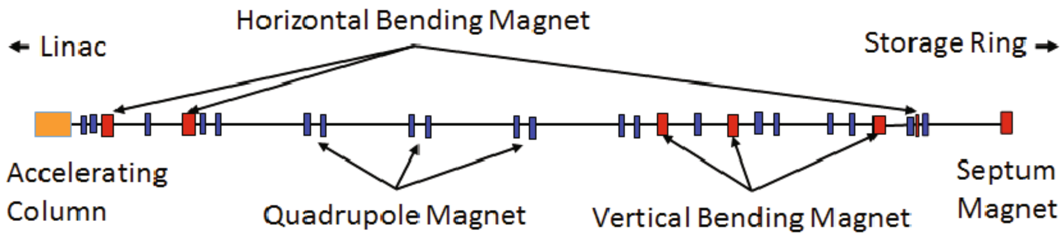

Fig. 1. (Color online) The layout of the PLS-II BTL. Three horizontal and three vertical bending magnets guide the electron beam for the injection to the storage ring.

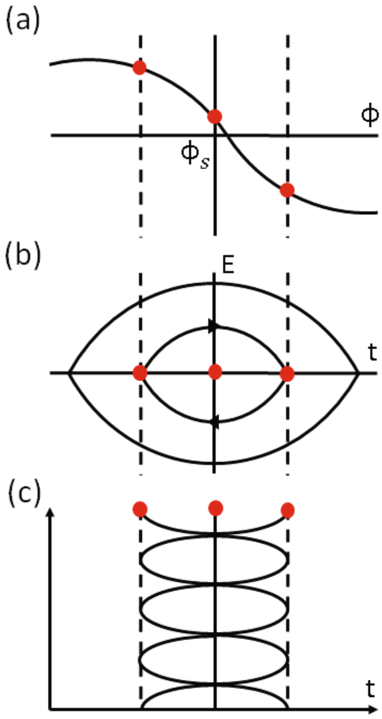

Fig. 2. (Color online) (a) Injected electron bunches and the storage ring RF field. ϕ_s is the synchronous phase and each bunch has 350 ps separation. (b) The synchrotron oscillation of injected electron bunches in the RF bucket. (c) Electron bunch trajectories in the time space. The horizontal and the vertical axes are a short time scale (< the storage-ring RF period) and a long time scale (> the synchrotron oscillation period), respectively.

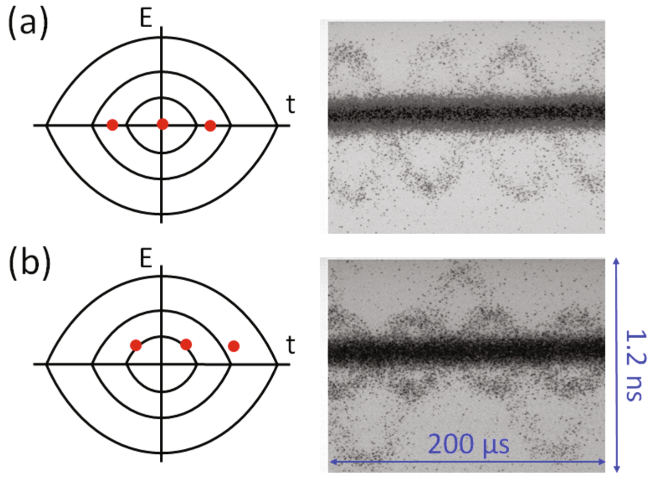

Fig. 3. (Color online) Electron bunches in RF buckets (left) and streak camera images at the injection (right). (a) Electron beam energy of 3 GeV, and (b) higher energy than 3 GeV cases are shown.

tal direction so that the energy stability of the electron beam is very important for the stable injection [2].

In addition to the transverse beam position at the injection point, the energy stability of the electron beam is critical for the longitudinal dynamics of the injection. In the PLS-II linac, a thermionic electron gun generates an electron beam and the electron beam is separated into three bunches after passing the pre-buncher and buncher. The separation between two bunches is 350 ps which is a period of the linac S-band RF. Because of the separations, arrival times of three bunches to the storage ring RF are different with each other and each bunch is accelerated to different energy. This time and energy exchange is continued in the RF bucket and makes the synchrotron oscillation as shown in Fig. 2.

To monitor the longitudinal motion of injected electron beams, we used a streak camera in a diagnostic beamline in the PLS-II storage ring [3]. Two inputs were applied to the streak camera for the electron beam imaging. One was a 10 Hz trigger for the slow sweep and the other was a 125 MHz signal for the fast sweep. The 10 Hz trigger was the same signal as the linac trigger for the electron beam generation, and the 125 MHz signal was generated from the RF frequency of 500 MHz. This means that the trigger and the sampling frequency of the streak camera were synchronized with the linac and the storage ring RF, respectively.

Figures 3(a) and 3(b) show injected electron bunches into RF buckets of the storage ring (left) and their streak camera images (right). The scales of the horizontal and the vertical axis are 200 μs and 1.2 ns, respectively. In an ideal case, as shown in Fig. 3(a), the electron bunches are injected to the center of the RF bucket and make the synchrotron oscillation. After the synchrotron damping time, all electron trajectories of the streak camera image are to be merged into the center line. When the linac

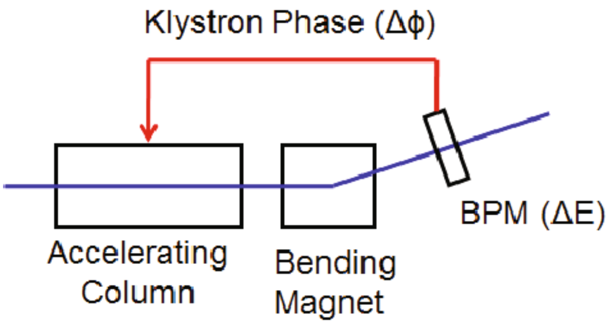

Fig. 4. (Color online) The working principle of the energy feedback system. If an energy difference of the electron beam is measured in a BPM after the bending magnet, a klystron phase can be changed to keep the same energy.

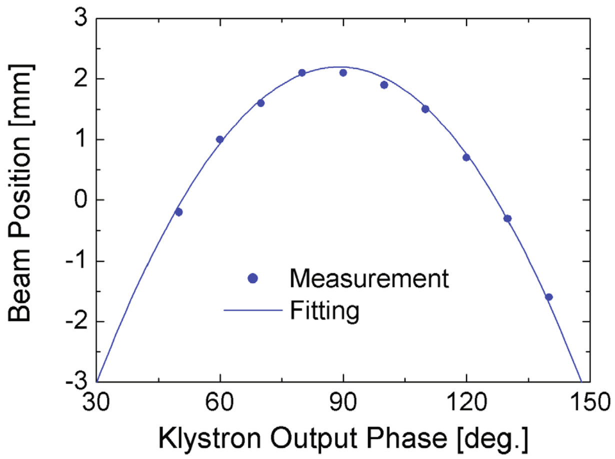

Fig. 5. (Color online) Measured beam positions after the bending magnet with different klystron phases. The maximum energy of the electron beam can be obtained at the crest phase.

beam energy is higher than 3 GeV, electron bunches have offsets from the RF bucket center as shown in Fig. 3(b). The energy difference makes arrival time change as well, so that offsets can be found not only in the energy axis but also in the time axis. Note that the outer electron bunch has a larger oscillation amplitude than that of the other electron bunches. If the linac beam energy is even higher than Fig. 3(b), the outer electron bunch cannot continue the synchrotron oscillation inside the RF bucket and fails to be injected into the storage ring [4].

III. ENERGY FEEDBACK SYSTEM

The working principle of the energy feedback system is shown in Fig. 4. The energy feedback system consists of a beam position monitor (BPM), an RF system, and an input output controller (IOC) for the feedback control. At the end of the PLS-II linac, bending magnets bend the electron beam trajectory, and a BPM after the bending magnet can measure the energy difference of the linac electron beam because of the dispersion. If the measured energy is different from the reference value, the RF power of the linac should be changed to keep the same energy of the electron beam. From sixteen RF systems in the PLS-II linac, the last RF system was selected to compensate the energy difference, while the other RF system are fixed. For the RF power control, either the voltage or the phase of the klystron output can be changed, but we decided to use the phase change because of the response time and the RF power stability. Measured data showed that the voltage change needed a longer response time than the phase change, and this made the energy feedback speed slow. In addition, if the required voltage was higher than the normal operation voltage, the klystron output power became unstable.

To determine the operation phase of the klystron for the energy feedback, a phase scan was performed. Figure 5 shows beam position changes according to different klystron phases. Both increasing and decreasing of the energy should be possible for the energy feedback so that an off-crest phase is required for the last klystron phase. Moreover, a plus offset phase (right-hand side of the crest phase in Fig. 5) is suitable to reduce the energy spread of the electron beam, because high energy electrons in the head will be less accelerated and low energy electrons in the tail will be more accelerated. Figure 6 shows transverse beam profiles by using the Optical Transition Radiation (OTR) [5]. The OTR screen monitor is located just after the BPM of the energy feedback system. Figures 6(a), 6(b), and 6(c) show beam images when last klystron phases are $-40°$ from the crest phase, crest phase, and $+40°$ to the crest phase, respectively. In the case of $-40°$ from the crest phase (left-hand side of the crest phase in Fig. 5), the beam size is longer than the other cases which means that the energy spread is increased.

For the energy feedback algorithm, a proportional-integral-derivative (PID) control method was applied. Figure 7 shows the measured beam fluctuation with different proportional gains. As the proportional gain increased, the beam stability became better, but it was saturated when the proportional gain was bigger than 8. On the other hand, the oscillation of the klystron phase was started with the proportional gain increase, and also saturated after the proportional gain of 8. Moreover, depends on the conditions, divergences of beam positions were observed with a larger proportional gain than 6, so that a small gain (less than 4) is being used in the normal operation.

Several linac conditions should be checked before the energy feedback running. For example, the electron gun must be turned on, and energy of the electron beam should be 3 GeV. In every loop of the energy feedback, the program checks the electron beam charge from the electron gun, and confirms that the calculated beam energy is 3 GeV by using the summation of klystron output

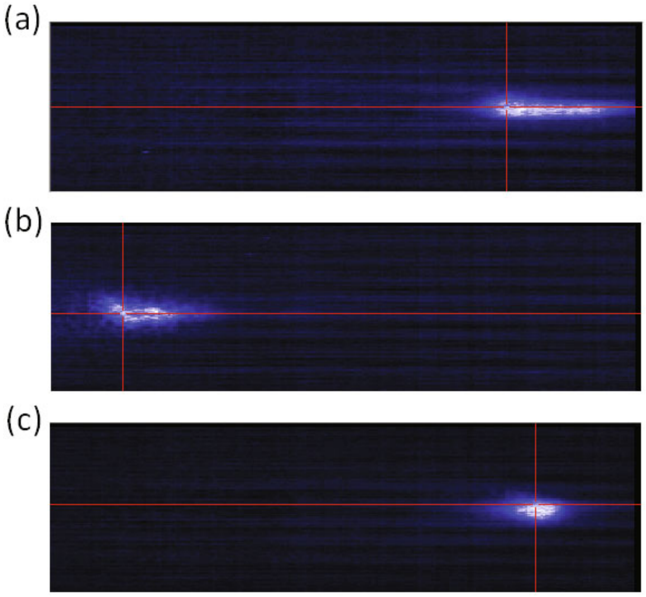

Fig. 6. (Color online) Transverse beam profiles from the OTR screen monitor with different klystron phases. Images of (a) -40° from the crest phase, (b) crest phase, and (c) $+40^\circ$ to the crest phase are shown.

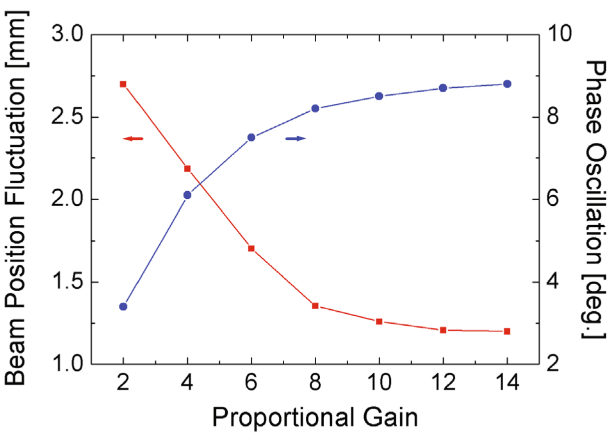

Fig. 7. (Color online) Amplitudes of the beam position fluctuation and the klystron phase oscillation with different proportional gains of the energy feedback. As the proportional gain was increased, the beam position fluctuation was reduced but the klystron phase oscillation was increased.

powers. In addition, the feedback program checks the bending magnet current at the end of the linac to guarantee that the electron beam goes to the BTL. There are maximum and minimum limits in the phase setting value for the klystron safety. If the difference between the measured beam position and the target value is too big, the feedback program skips the klystron phase change to avoid unnecessary fluctuation. Finally, if there is a fault in a linac RF system which makes the beam energy drops, the feedback program waits for 30 seconds for the recovery.

Figure 8(a) shows BPM readings during one hour with

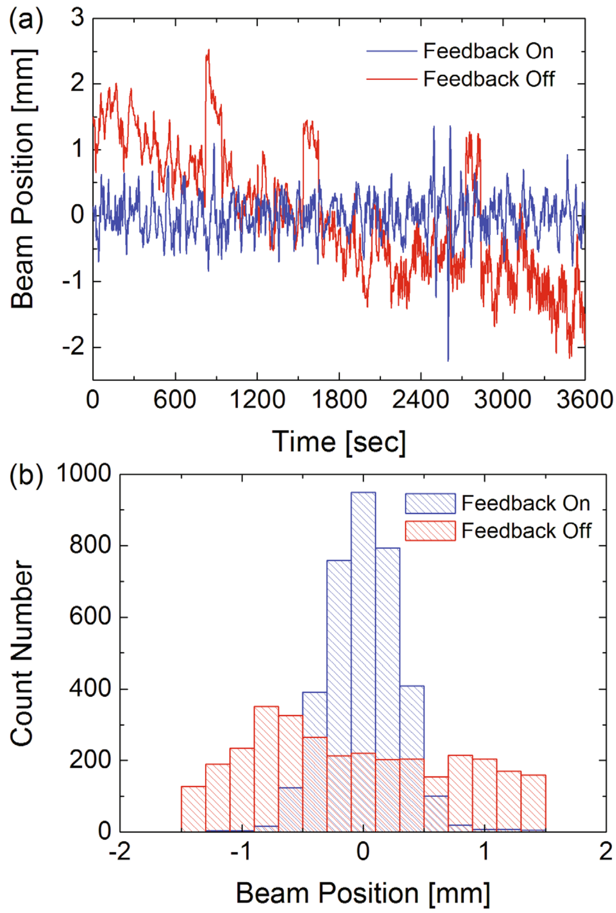

Fig. 8. (Color online) (a) Measured beam positions during one hour with and without the energy feedback system, and (b) a histogram of beam positions with the results of (a). The drift of the electron beam position was removed when the feedback was turned on.

(blue line) and without the energy feedback system (red line). Figure 8(b) shows a histogram of beam positions in the results of Fig. 8(a). Note that the position drift of the electron beam was removed when the feedback was turned on. The measured energy jitter with the energy feedback system was less than $\pm 0.1\%$ (rms) and it met the requirement of $\pm 0.2\%$ (rms) for the PLS-II linac. However, the position fluctuation itself was not removed even with the energy feedback system. The repetition rate of the PLS-II linac and the BPM reading were 10 Hz so that the feedback frequency was also limited to less than 10 Hz. This means that the bunch by bunch energy fluctuation was not corrected, but the beam energy drift was removed by using the energy feedback system.

IV. FUTURE WORK

The energy feedback system uses the BPM reading after the bending magnet to measure the electron beam energy. Here, it is assumed that the electron beam position before the bending magnet is ideally stable. In reality, however, the electron beam position has jitter so that errors can be generated in the energy measurement. This means that the electron orbit feedback in the linac is needed for a better performance of the energy feedback. In addition, a beam-based-alignment should be done to help the orbit feedback. The electron beam passes through the quadrupole center after the beam-based-alignment, and the beam position change from the quadrupole kick can be minimized in the case of the beam energy fluctuation. After that, the orbit feedback makes the electron orbit as close as possible to the reference one and keeps the beam position stable before the bending magnet at the linac end.

V. SUMMARY

For the PLS-II top-up operation, an energy feedback system was installed to make a stable injection to the storage ring. A BPM after a bending magnet at the linac end measured the beam position and the last klystron phase was changed to compensate the energy difference from the reference value. A PID control algorithm was used for the feedback, and various conditions and limits were applied to the feedback program for the machine safety. After the installation of the energy feedback system, the beam position drift was removed and $\pm 0.1\%$ (rms) energy stability was achieved for the stable injection of the top-up operation.

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