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Present Status of the Electron Beam Diagnostics System of the PLS-II Linac

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The PLS-II, the upgraded PLS (Pohang Light Source), has been providing users with photon beams in the top-up mode since March 2013. The requirements for the PLS-II linac to achieve the top-up injection are very demanding because it is a full energy injector with a very limited energy margin. One of the requirements is to ensure high injection efficiency in order to minimize the beam loss at the storage ring injection point and the experimental hall during injection because loss leads to a high radiation level in the experimental hall. The energy stability and energy spread of the accelerated electron beam are fundamental parameters to monitor and manage for high injection efficiency. An energy feedback system consisting of a stripline-type beam position monitor and the last klystron was implemented. To diagnose the injected beam's energy and energy spread in real time during top-up mode injection, we installed an optical transition radiation (OTR) monitor system upstream of the beam transport line (BTL) after the first bending magnet. The energy and the energy spread ranges can be controlled with a horizontal slit installed after the OTR monitor. The vertical beam size of the accelerated beam must be decreased for efficient injection because the electron beam is injected into the storage ring with many in-vacuum undulators of small gaps. For this purpose, two vertical slits were installed in the BTL region. We will describe mainly those instruments closely related to top-up operation, though other beam diagnostic instruments have been used since PLS.

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I. INTRODUCTION

The PLS-II (Pohang Light Source II) is a 3rd generation synchrotron accelerator upgraded from the PLS (Pohang Light Source), which had operated for more than 15 years. The main goals of the upgrade among others are to increase the beam energy from 2.5 to 3.0 GeV, to provide high brilliance photon beams for the users, which involves changing the lattice to reduce the beam emittance and introducing more insertion devices, and to operate in the top-up mode [1,2]. From the viewpoint of the linac, the first and the third goals present demanding tasks to the linac. The PLS-II linear accelerator is a full-energy injector, and considerable efforts, such as adding new klystron-and-modulator systems and accelerator columns, and operating at higher klystron powers to name a few, were made to increase the beam energy by 500 MeV in the same linac length [3,4].

In top-up operation, electron beams are frequently injected to keep the stored beam current in the storage ring (SR) constant. The operation mode is beneficial to the accelerator machine, as well as the beamline, because it obviates deleterious heat load effects from the stored beam current variation, which, in turn, contributes to the stability of the stored beam. The top-up operation of the PLS-II for users started in March 2013 with a stored beam current of 120 mA. The current has been increased gradually with improvements in the machine's performance and stability. At present, the stored current is 230 mA and will continue to increase to the final design value of 400 mA step by step. In the present time-based top-up mode, the beam is injected every three minutes. Figure 1(a) shows the beam current stored in the SR for two days in the top-up operation mode, and the details of the first 150 minutes are shown in Fig. 1(b). The beam current is shown to be maintained within about 0.3%. The stored beam is maintained fairly stable except for occasional small dips from injection skips due to temporary malfunctions of the linac RF system or other causes. Figure 1(c) shows the injected beam-charge during this period. The charge varies between 20 and 30 pC/pulse.

One of the benefits of the top-up operation is that beamline experiments can be performed without interruption during beam injections; therefore, beam loss must be as low as possible during injection to ensure that the radiation level is below the allowable value. The

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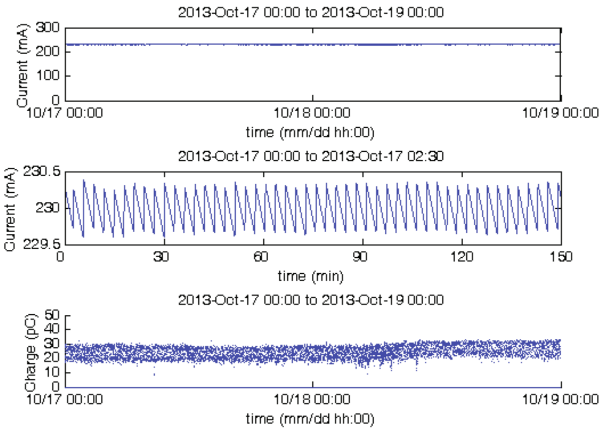

Fig. 1. (Color online) (Top) Stored beam current in the SR during two days, (Middle) the first 150 minutes, and (Bottom) the charge of the injection beam.

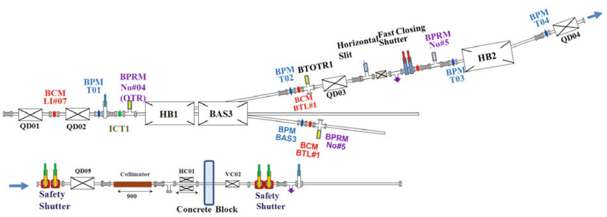

Fig. 2. (Color online) Layout of the diagnostics in the beginning of the beam transport line.

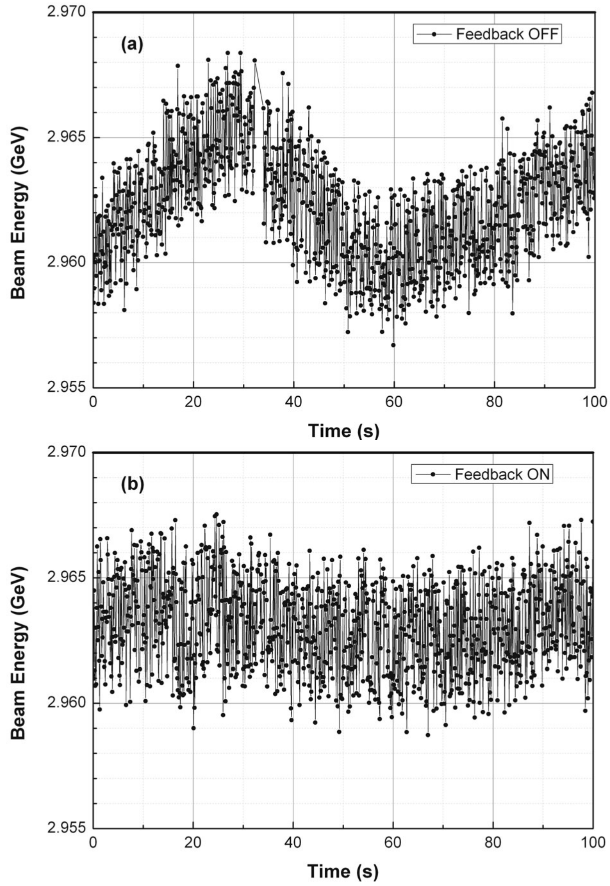

Fig. 3. Curing of the energy fluctuation by the energy feedback system (a) with energy feedback off and (b) with energy feedback on.

PLS-II was operated in the decay mode in the first year because the radiation level in the experimental hall exceeded the limit. In the meantime, many efforts were made to improve the injection efficiency and reduce the radiation level. The top-up operation required a substantial improvement in the linac's energy stability and beam characteristics, and several instruments for diagnosing them were installed. In this article, we will describe mainly the linac diagnostic instruments upgraded or newly installed for the top-up operation.

II. BEAM DIAGNOSTICS OF PLS-II LINAC

1. Energy Feedback

For reliable and efficient top-up operation, stabilizing the linac beam energy is essential. An energy feedback system is required to suppress the energy variation with a period of tens of seconds or more. The energy feedback system consists of the last klystron of the linac and a beam position monitor (BPM) of the stripline type installed upstream of the beam transport line (BTL). Figure 2 shows a schematic layout of the starting point of the BTL. The BPM (BPM T02) is installed in the dispersion region after the first horizontal bending magnet, HB1, to deflect the beam from the linac to the BTL. The orbit information read in a Libera Brilliance beam position processor (Instrumentation Technologies [5]) connected to the BPM is used to adjust the phase of the last klystron.

In the present time-based top-up injection mode, the electron beams are injected every 3 minutes. The energy feedback is performed for 40 seconds before the start of each injection. During the feedback period, the electron beam is prevented from injecting to the SR by two sets of dual safety shutters of which one set is for redundancy. A fast closing shutter serves to rapidly block beams ahead of the safety shutters in an emergency.

Figure 3 shows an example of the performance of the energy feedback system. The electron beam's energy fluctuates with period of about 80 seconds and is accompanied by a temporary variation in the cooling temperature of the accelerating columns. The energy fluctuation is shown to be cured by the feedback system. In this case, the relative rms energy variation was decreased from 0.078% to 0.064%. The rapid pulse-to-pulse energy jitters, which are caused by accelerating systems such as the rf system or the magnet power supplies, are not the object of the feedback system. An effort to reduce these energy jitters is being made separately.

2. Beam Current Monitor

During the first half year of the PLS-II, we used the same gun as used in the PLS and a grid pulser of 1 ns (FWHM), and the number of bunches was five [4]. The designed RF bucket width of the SR is about 1.1 ns, and considering beam jitters, three bunches at most can be injected stably in a single bucket. These extra bunches contributed to the high radiation level in the experimental hall from beam loss at the SR injection region. A shorter beam pulse was proven to be desirable for efficient top-up injection. The top-up mode operation causes the e-gun cathode's lifetime to be shorter than the decay mode, so a second e-gun is often equipped to switch immediately from one to the other in an emergency. Instead, we adopted a 'dual vacuum valve system' [4] to save time to change the cathode. In this scheme, an additional vacuum valve was added near the existing valve separating the vacuum of the e-gun and the bunching section. When the e-gun is replaced with a standby e-gun, only the short section between the two valves is exposed to air. However, the scheme was found to deteriorate the bunching process because the increased drift length in the low-energy section caused the beam to defocus significantly and to lengthen because of the relatively low e-gun accelerating voltage (80 kV). We chose to restore the layout to the original layout. After operation for half a year, the old e-gun was scrapped because the deposition of the cathode material on the ceramic insulator caused high-voltage leakage. A new e-gun was designed, and the cathode assembly was changed from an Eimac Y-824 to Y-845, which has four times smaller cathode area. Furthermore, we used a Kentech grid pulser of 250 ps for shorter electron beams to reduce the number of bunches.

To measure the beam current in the pre-injector we use two fast current transformers (FCT, Bergoz Instrumentation [6]) with a bandwidth up to 2 GHz. One is placed near the exit of the e-gun and the other is at the end of the pre-injector of 100 MeV. By comparing the two FCT outputs we can examine the optimum bunching condition. Figure 4(a) shows the beam's pulse signal observed in the first FCT. The beam's pulse length is about 500 ps (FWHM) and the charge is about 300 pC. At the end of pre-injector, we have a bunch measurement system consisting of an OTR target and a streak camera. Unfortunately, we were not able to measure the bunch structure or bunch length because of too-weak OTR light intensity from a small charge and the degraded performance of our streak camera. We used a wideband oscilloscope (Agilent 90604A, 6 GHz, 20 GS/s) with a wall current monitor (WCM) to observe the beam's structure. Figure 4(b) shows the bunch structure observed with a wall current monitor located at the 1.8-GeV position. The oscilloscope is located about 50 m away from the monitor. Although the attenuation of the high-frequency components along the cable broadens the peaks, the bunch structure can be discerned. Three major bunches and a negligibly small bunch (shown with arrows) can be recognized about 350 ps separated from each other. The fourth bunch is very weak in view of the background level.

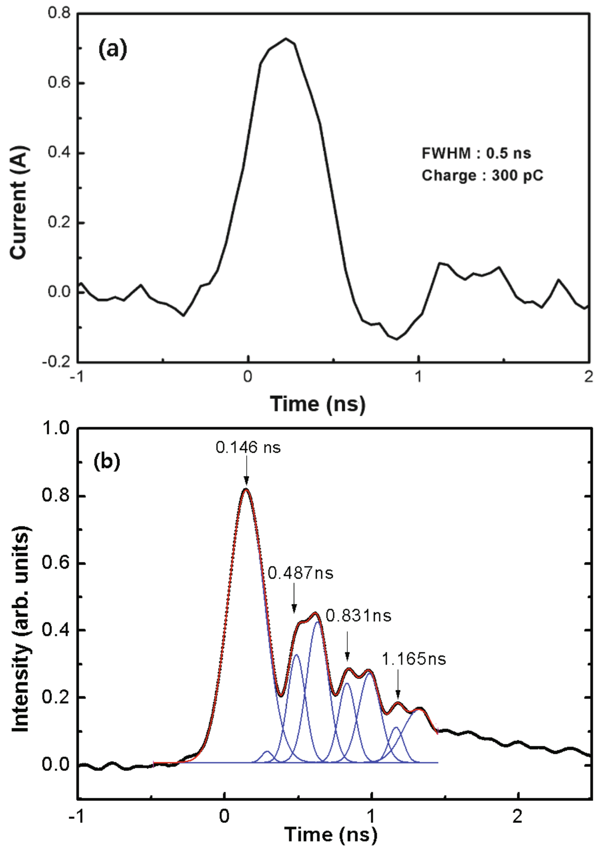

Fig. 4. (Color online) (a) Shape of the electron beam pulse from the e-gun. (b) Shape of the bunched beam pulse observed with a wall current monitor.

The injection efficiency indicates the ratio of the increase in the stored beam's current to the injection beam's current measured at the end of the BTL. The latter is measured with a stripline BPM in the end of the BTL and a Libera Brilliance processor which supplies beam-charge information proportional to the sum of the values from the four stripline electrode signals. The absolute charge value was calibrated with an integrating current transformer (ICT, Bergoz instrumentation) installed near the BPM. As shown in Fig. 1, the injected beam charge is about 20 to 30 pC in normal top-up mode.

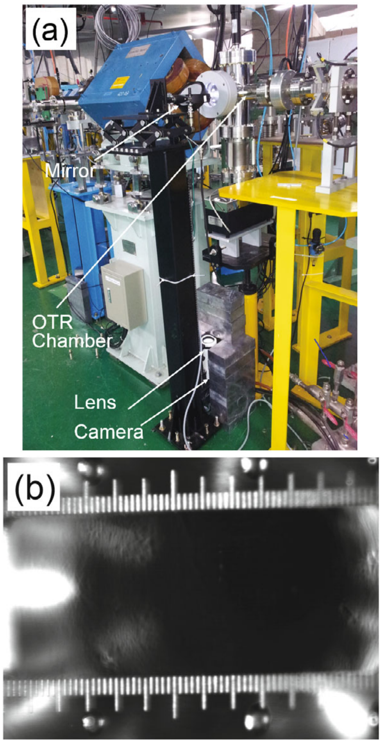

Fig. 5. (Color online) Photos of (a) the OTR monitor system and (b) the OTR target as installed. The reflected image of the beam pipe is shown.

3. Optical Transition Radiation Monitor

As mentioned previously, the electron-beam energy feedback is performed with the BPM T02, installed after HB1. Such a BPM detects the beam charge center and serves well as an energy feedback device. Along with the beam energy, the energy spread has a great effect on efficient beam injection into the SR. For the purpose of monitoring the energy spread of the electron beam, we inserted a thin-film optical transition radiation (OTR) monitor system (BTOTR1) after HB1 (see Fig. 2). The OTR system in the tunnel is shown in Fig. 5(a). The OTR target was made of thin aluminum of 580 nm in thickness coated on a polyimide film of 25 μm (Fig. 5(b)). An analytical analysis indicated a negligible effect on the emittance of the 3-GeV electron beams passing through the film [7]. This enabled us to make measurements of the in-situ beam energy and energy spread in the top-up mode injection. The target's dimensions are 70 mm (H) $\times$ 20 mm (V). A camera (SONY XC-HR50) is installed inside lead blocks near the ground to protect it from radiation damage, and a mirror is used to reflect the OTR downward. Because the OTR from the 3-GeV electron beam is emitted in a very narrow angle ($1/\gamma$, about 1/6000 radian), the orientation of the mirror can be steered remotely to direct the OTR to the camera correctly. The camera is operated in progressive scan mode, and its shutter is triggered by using the beam trigger to synchronize the camera to the OTR emission and to reduce the noise from stray light. A lens (f = 120 mm, ϕ = 50 mm) is used to magnify the image of the target. The energy spread resolution of the system is 0.0125%.

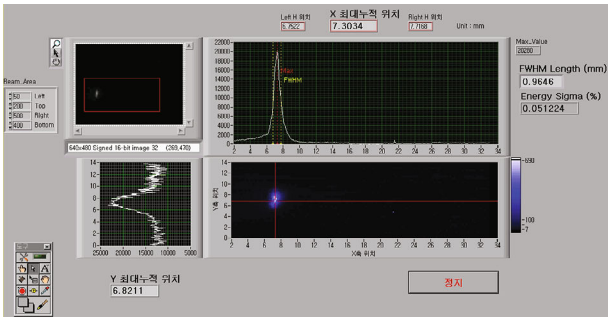

Fig. 6. (Color online) OTR image analysis program. The upper left panel shows the camera image, and the region inside the red rectangle is magnified in the lower right panel and is integrated to get the intensities along the horizontal and the vertical pixels.

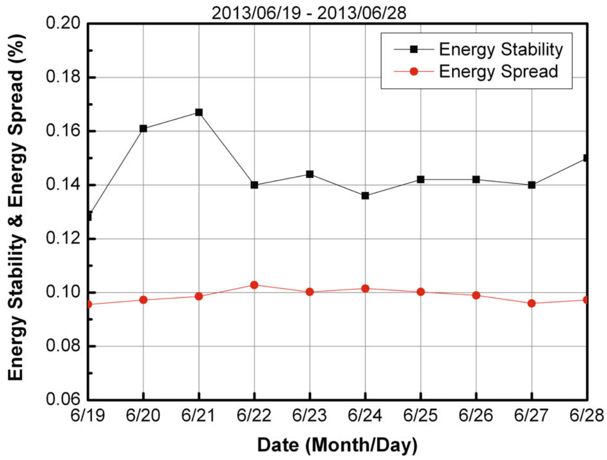

Fig. 7. (Color online) Long-term energy stability (RMS) and energy spread (RMS) measured with a thin-film OTR monitor in the top-up mode.

The OTR image is captured by using a NI PCI-1410 (National Instruments) image acquisition board. The image is analyzed using a LabVIEW program. The graphic user interface of the program is shown in Fig. 6. The energy stability and the energy spread are measured using the peak position variation and the width of the profile respectively. Figure 7 shows an example of the long-term energy stability and energy spread observed with the OTR monitor in the top-up mode. The energy and energy spread can be seen to have been maintained very stably on a long-term base. The one-minute short-term energy stability was about 0.04%, and the energy spread was almost the same. The energy stability was improved greatly after the de-Q'ing systems had been applied to the modulators for high-voltage regulation [8].

Table 1. Diagnostic instruments of the PLS-II linac.

Instrument	Number		Remark
	Linac	BTL	
Beam Current Monitor	9 (7 + 2)	5	(WCM + FCT)
Beam Profile Monitor	10 (4 + 6)	6 (5 + 1)	(Fluorescent screen + OTR)
Beam Position Monitor	12	14	
Beam Charge Monitor	1	1	ICT
Beam Loss Monitor	42	12	
Beam Slit	1	3 (1 + 2)	(Horizontal + Vertical)

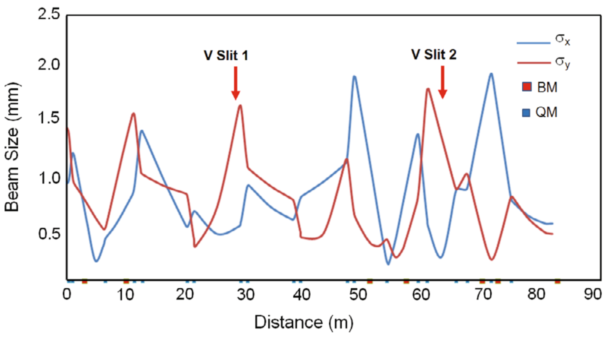

Fig. 8. (Color online) Electron-beam sizes along the BTL. The positions of the two vertical slits are shown.

4. Slit System

We installed a horizontal slit and two vertical slits in the BTL region of the PLS-II linac. The horizontal slit is situated at an upstream point of the BTL with a large dispersion function in order to inject only electron beams within the energy acceptance range of the SR. It also reduces the energy spread by passing the portion of the beam with adequate energies and cutting off the remainder. A horizontal slit had been also used in the PLS, but we improved the structure for accurate control of the slit. In the PLS, the actuating axes of the blades were collinear, and the slit occasionally got stuck because of collisions by accident when we tried to set it to a very small aperture. Therefore, the blade structure was designed so that two blades could overlap each other and setting them to a small aperture or blocking the beam completely was possible. The slit blades are made of 12-mm-thick tungsten blocks, which correspond to about four radiation lengths for a 3-GeV electron beam. A fluorescent screen was attached on the front face of each blade to monitor the beam impinging on a slit blade. We used a precision linear motion guide with stepping motors with a gear ratio of 10. It has a sub-micron resolution, and a test showed repeatability of less than 2 μm. The vertical slits described below also have almost the same structures.

One of the most distinctive features of the PLS-II, as opposed to the PLS, was to introduce in-vacuum undulators in numbers to provide users with high-brilliance photon beams in hard X-ray. A total of 10 in-vacuum undulators started to operate, with most of them operating in minimum full gaps of 6 mm. These small physical apertures of undulators caused significant beam losses in some undulators and caused high radiation-dose levels so that the top-up injection was prevented in the first year of the PLS-II operation. Reducing the vertical beam size of the injection beams was essential. To cope with this problem, we inserted two vertical slits in the BTL. The installation points were selected so that the vertical beam sizes were large and the phase advance between them was close to $\pi/2$ radian (Fig. 8). The designed beam sizes at these points are 1.6 mm and 1.4 mm, respectively. The horizontal and vertical slit system enabled us to increase the injection efficiencies to 60 $\sim$ 70%, almost double the amount without the slit system, which led to a reduction in the radiation level near the in-vacuum undulator beamlines to below the restriction level.

Up to now, we have described mainly the diagnostic instruments installed for the top-up operation. The PLS-II linac includes additional diagnostic instruments which have been used since the time of the PLS. The overall diagnostic instruments are listed in Table 1.

III. CONCLUSION

A couple of diagnostic instruments were installed in the linac BTL for stable top-up injection to the PLS-II storage ring. A thin-film OTR is useful for in-situ monitoring of the energy and the energy spread and gives the instant information on the working status of the linac components. A horizontal slit and a set of two vertical slits were installed to improve the injection efficiency and reduce the radiation level in the experimental area. The slit system served to increase the efficiency by a factor of two and made operation of the top-up injection mode possible. The energy feedback system successfully kept the linac energy constant. Many R&D efforts, however, remain to be done in the PLS-II linac diagnostics, for example, reliability improvement of diagnostic instruments and beam-based alignment (BBA) in the linac and BTL.

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