UPGRADE OF POHANG LIGHT SOURCE (PLS) LINAC FOR PLS-II*

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Abstract

Since its completion in 1993, the PLS (Pohang Light Source) linear accelerator has been operated as the full energy injector to the PLS storage ring - a 2.5-GeV 3rd generation light source in Korea. After successful services for more than 15 years to the Korean synchrotron radiation users' community, the PLS is now being upgraded to meet ever-increasing user demands for brighter lights. The PLS-II, the major upgrade program to the PLS, is to increase the beam energy to 3 GeV, changing the storage ring lattice to accommodate large number of insertion devices with lower emittance, and to have the top-up injection as the default operating mode. In order to achieve high injection efficiency, beam qualities including the energy spread, pulse length, and jitters in bunch arrival times to the storage ring rf bucket have to be reduced. After successful upgrade of the PLS linac one could further exploit its potential by, for example, implementing high-brightness electron source, which would open up new possibilities with the facility.

INTRODUCTION

Since its completion in 1994, the Pohang Light Source (PLS) has provided brilliant lights to Korean science communities. To meet ever-increasing users' demands for higher-quality lights, PLS performances have been steadily improved. As an example see Fig. 1 for improvements in machine availability, mean time between failures (MTBF), and user beam time since 1988. As the result of those efforts the PLS is now running 30 user beam-lines accommodating > 2500 users (>20% annual increase since 2000) every year. But the needs for brighter lights (especially for insertion device (ID) beam-lines) from user communities are already exceeding the capability of the PLS. Also recent constructions of mid-energy synchrotron lights sources in the world including ALBA, SPEAR-3, SSRF, SOLEIL, DIAMOND, and ASP have greatly motivated the construction of a brighter light source in Korea. And the decision was to construct a new storage ring (named as PLS-II storage ring) with the energy of 3 GeV, lower-emittance lattice with more straight sections for accommodating maximum 20 IDs, and superconducting RF cavities to support 400-mA stored current. It will be built within existing building and utilize existing linear accelerator with energy upgrade to 3 GeV (named as PLS-II linac). Because the PLS-II will be operated in the top-up injection mode the PLS-II linac has to provide beams with stable energy and low energy spread (0.2% rms). This will be achieved by demonstrating the top-up operation in PLS (before PLS-II). Table 1 summarizes the history of PLS construction and upgrades.

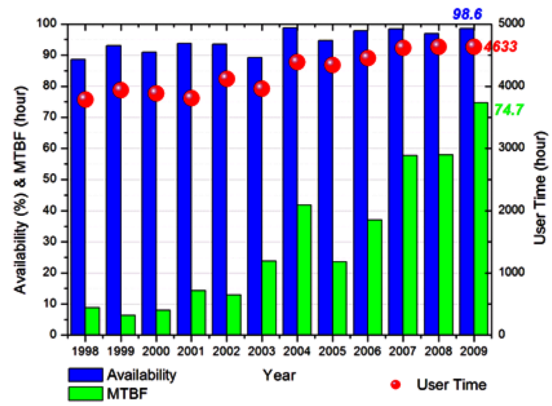

Figure 1: Improvements in PLS availability, mean time between failures (MTBF), and user beam time since 1988.

Table 1: History of PLS Construction and Upgrades

PLS Construction	Project Start	Apr. 1, 1988
	Ground Breaking	Apr. 1, 1991
	2-GeV Linac Commissioning	Jun. 30, 1994
	2-GeV Storage Ring Commissioning	Dec. 24, 1994
	User Service Start	Sep. 1, 1995
	Ramping to 2.5 GeV	Sep. 1, 2000
	Direct Injection at 2.5 GeV	Nov. 1, 2002
Major Upgrade to PLS (PLS-II)	Project Start	Jan., 2009
	Top-Up Operation in PLS	Oct. 2010
	Project Completion	Dec., 2011

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PLS-II LINEAR ACCELERATOR

The electron gun for the PLS as well as the PLS-II is the triode type with a 250-ps grid pulser to generate <1 ns pulses to be fitted into storage ring rf buckets (~1.5 ns). Gun vacuum is improved to enable gun gate valve to be always open for supporting top-up operation. Bunching system includes a standing-wave pre-buncher (2,856 MHz), a 4-cell travelling-wave buncher (0.5c → 0.75c), and two accelerating columns. With proper operating condition it can generate 80-MeV beams with <10-ps micro-bunch length. Measured transverse emittance, though not exact, was ~150 mm mrad. We would have similar value in the PLS-II linac. One of the most important parameter for the PLS-II linac is the energy spread which should be less than 0.2% rms for efficient injections to the storage ring. Also the energy stability should be as good as 0.2% rms for stable top-up operation. Parameters for the PLS-II linac are summarized in Table 2.

Table 2: PLS-II Linac Parameters

Beam Energy	3 GeV
Operating Frequency	2856 MHz
Transverse Emittance	25 nm rad
Energy Spread	rms 0.2%
Beam Pulse Length	< 1 ns
Peak Beam Current	~1 A
Machine Length	~160 m
Number of Accelerating Columns	46
Number of Klystrons	16
SLED Energy Gain	~1.5
Energy Stability	rms 0.2%

Low energy spread is obtained by reducing micro-bunch length which is determined by the velocity and phase of particles at the entrance of and field gradient of the first accelerating column [1]. Also it is recommended to operate at the crest phase. But these conditions are not always satisfied, and to ensure low energy spread, we have installed a slit at a dispersive section in linac-to-ring transfer line. In PLS there is a vacuum-isolation window (made of 0.2-mm thick stainless steel sheet) which spoils transverse emittance degrading the injection efficiency. In PLS-II we will implement differential pumping system near the transfer-line-to-ring junction to remove the window.

Transverse optics is not much changed except the end of the linac where two accelerating columns are added for increasing the energy. For this we have to remove two out of four matching quadrupoles which would necessitate more careful management of the transfer-line optics. Figure 2 shows PLS and PLS-II linac lattices.

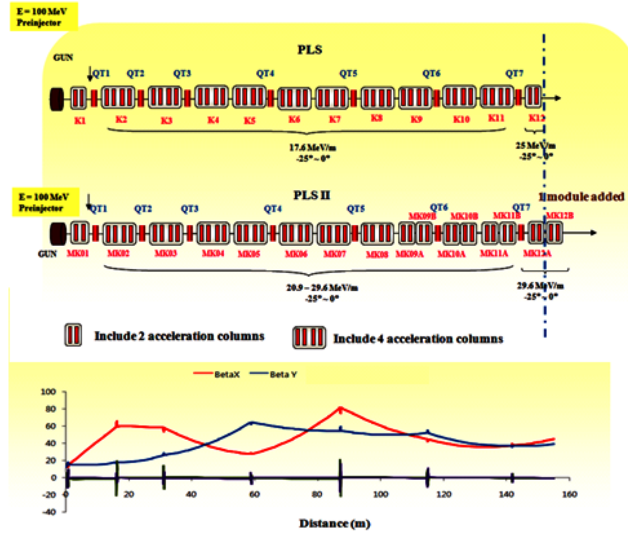

Figure 2: Lattice Layouts of PLS and PLS-II Linacs.

The PLS-II linac will utilize existing accelerating columns (2π/3-mode constant-gradient accelerating structures provided by the IHEP, China) and SLED cavities. 12 klystrons (1 SLAC5045 and 11 Toshiba E3712s) will be re-used. In PLS four accelerating columns are connected to a klystron (except the first and last klystron where two accelerating columns are connected to a klystron). Energy gain for one klystron section is about 225 MeV. In order to obtain 3-GeV energy with the same machine length we will modify waveguide networks for the 9th to 11th klystron sections to connect two accelerating columns to a klystron. We also increase klystron operation power up to 70 MW (from 55 – 60 MW in PLS) to get average accelerating gradient 29.6 MV/m. Operational stabilities at this gradient have been tested in this year with promising result. Parameters for the PLS and the PLS-II linacs are summarized in Table 3.

Table 3: Comparison of Linac Parameters for PLS and PLS-II

PLS

	MK1(1set)	MK2 - MK11(10set)	MK12(1set)
RF Power	55 MW	55 - 58 MW	56 MW
Klystron	SLAC5045	Toshiba E3712	
A/C	IHEP		Mitsubishi
SLED Gain	-	1.5	1.5
Gradient	17.6 MeV/m	17.6 MeV/m	25 MeV/m
Energy	105.8 MeV	224.5 MeV per module	150 MeV
Number of A/C's	2	40	2

PLS-II

	MK1(1set)	MK2 – MK08(7set)	MK09A-MK11B(6set)	MK12A-MK12B(2set)
RF Power	60 MW	70MW	70 MW	70 MW
Klystron	SLAC5045	Toshiba E3712		
A/C	IHEP			Mitsubishi
SLED Gain	-	1.5		1.5
Gradient	18.3 MeV/m	20.9 MeV/m	29.6 MeV/m	29.6 MeV/m
Energy	105.8 MeV	251.0 MeV per module	177.5 MeV per module	177.5 MeV
Number of A/C's	2	28	12	4

Figure 3 depicts energy upgrade scheme for the PLS-II linac. We aim to achieve energy margin of 9.5%. In the 1st klystron section two accelerating columns are connected. From the 2nd to 8th and 9th to 16th sections 4 and 2 accelerating columns are connected respectively. In PLS-

II we will have 4 accelerating columns provided by the Mitsubishi Heavy Industries.

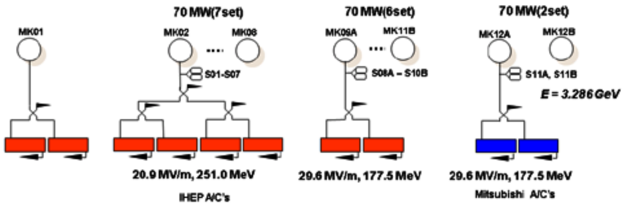

Figure 3: Energy Upgrade Scheme for PLS-II Linac.

UPGRADE ACTIVITIES IN 2010 SUMMER

Linac upgrade for the PLS-II should be finished well before the commissioning start of storage ring which is scheduled in July 2011. Many upgrades have been done during summer maintenance in this year including extensive renovation of cooling, LLRF, and timing systems. As the result linac energy stability has been greatly improved enabling successful top-up test operation in the beginning of this September.

RF linacs employ many resonant devices such as accelerating columns, SLED cavities, and klystrons. Stability of their operation critically depends on environmental temperatures with their sensitivities depending on their quality factors (Q values). The most sensitive device is SLED cavity which has Q value > 15,000. Table 4 shows measured temperature sensitivities for SLED and klystron in the PLS linac [2].

Table 4: Sensitivities of PLS Linac RF Devices on Utility Temperatures

Device Parameters	Sensitivities	Utility parameters
SLED output phase	$3^o/^oC$	Air temperature
SLED output phase	$10^o/^oC$	Cooling water temperature
Klystron output phase	$1^o/^oC$	Cooling water temperature

Most of normal-conducting RF devices are water cooled and the cooling-water temperature is usually the most important environmental factor determining their stabilities. But RF devices operating the linac gallery experience air temperature variations and this has been another important factor in PLS linac. Regulation of air temperature in the linac gallery has not been easy as contrast to the linac tunnel where human access is prohibited during operation and airtight condition is secured. The problem has been solved by installing thermal insulation boxes surrounding all SLED cavities.

We completely renovated precision cooling system to provide independent stations for each SLED cavity. As the result we have achieved temperature stabilities better than +/- 0.1 ^oC for every SLED cavities as well as accelerating columns. Figure 4 shows 15-min temperature stabilities of all SLED cavities.

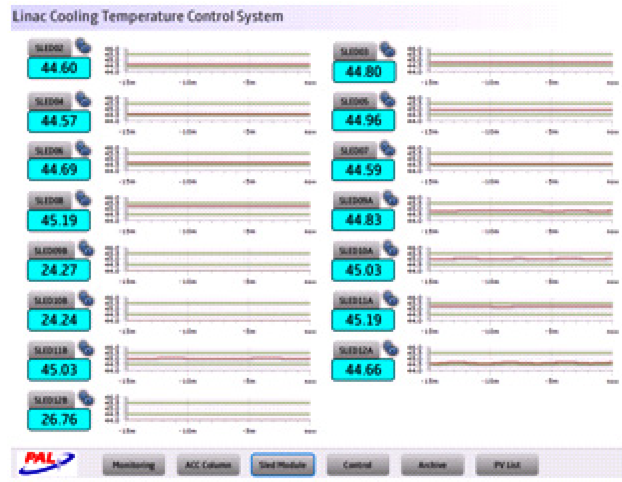

Figure 4: Temperature stability of PLS/PLS-II linac SLED cavities. Sensors are installed at cavities surfaces. SLEDs 09B, 10B, and 12B are not installed yet and their temperatures shown here are for cold waters before mixing with hot water.

We modified waveguide network in the 11th klystron section to add one more klystron (Toshiba E3712). This necessitated replacement of existing modulator by compact one powered by inverter HVPSs. See Fig. 5 for the views of 11th klystron station before and after the modification. At the time of this writing the linac is operating at 2.5 GeV without the 11th station by increasing RF powers for the other stations each up to 70 MW (except the 1st one). RF processing is being done during user operation which necessitates maintaining the 11th station's phase to 0. This is accomplished by digital LLRF system with phase feedbacks.

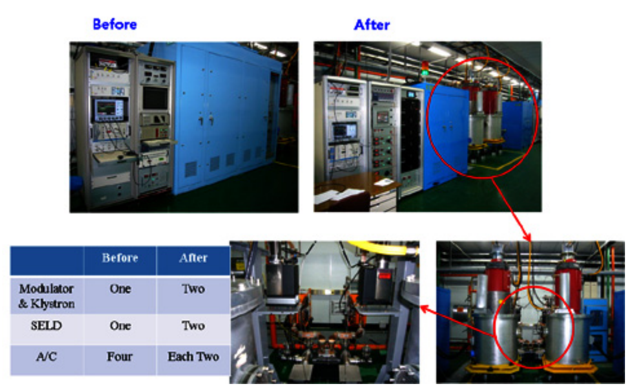

Figure 5: Doubling RF Power for PLS-II Linac.

The role of the linac LLRF is to provide the isolation of microwave drive line from and the correct RF phase & amplitude adjustment to the klystron input cavities. With the digital IQ modulations/demodulations and the feedback controls RF phases are maintained to the set values against changes in klystron voltages and environmental conditions. The reference signal (2,856 MHz) is provided by a temperature-stabilized coaxial cable. Figure 6 is the LLRF control panel of which bottom plots show phase stabilities for each klystron station.

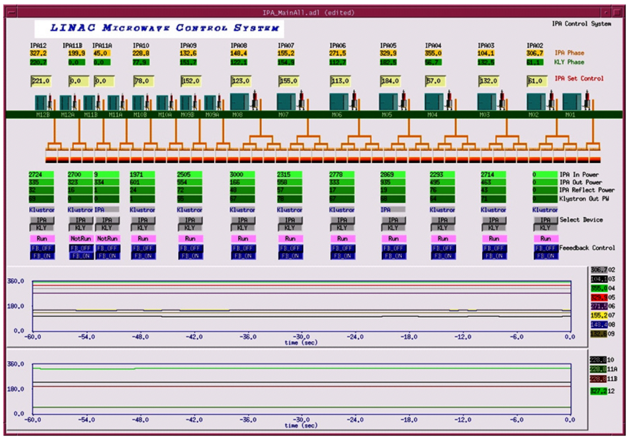

Figure 6: Control Panel of Upgraded LLRF System.

For short gun pulse length of <1 ns, the jitters in beam arrival times to the bunching system cause beam-to-RF phase jitters and finally result in energy jitters. The magnitude of the beam-to-RF phase jitter is smaller than the gun timing one by the factor of the bunch compression. For the PLS linac bunching system the bunch compression factor is roughly 15. Therefore in order to get <1 ps beam-to-RF phase jitter the gun timing jitter should be less than 15 ps. The measured gun timing jitter was about 25 ps rms for the PLS linac timing system. For the PLS-II we will adopt the event trigger system co-developed with the SSRF in china. Recent beam test of the system showed encouraging result. The short-term gun timing jitter was < 10 ps rms as is shown in Fig. 7.

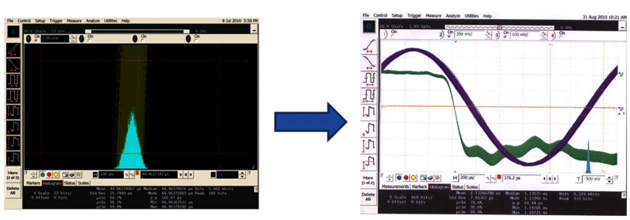

Figure 7: The result of gun timing jitter measurement for the PLS (left) and PLS-II timing systems (right). The PLS-II timing system is based on the Event Trigger system co-developed with the SSRF in China.

We have measured the energy stability of the PLS linac using a digital BPM (Libera Single Pass provided by the Instrumentation Technologies in Slovenia [3]) installed at the beam analysing station #3 (BAS3). The BAS3 consists of a bending magnet, a strip-line pick-up, beam screens, beam charge monitors, and a beam dump. Dispersion at the strip-line location is 250 mm. The digital BPM can acquire beam positions at the rate of beam repetition (10 Hz). 5-min beam-position samples acquired at the BAS3 BPM in the beginning of this September are plotted in Fig. 8. Standard deviation of the beam-position distribution was about 0.5 mm which is translated into the rms energy jitter of about 0.2%. This is compared to the value of 0.36% measured in this July. The difference is believed to be from different linac operation conditions. For example the September measurement was done with all klystron stations on the crest phase (except the 11th station which was turned off) and higher RF power levels than the July measurement. It is known that linac operation with the on-crest phasing and higher klystron RF powers (especially true for Toshiba E3712 klystrons [4]). Refinement of the measurements should be done to include the errors in the BAS3 optics and beam instrumentations.

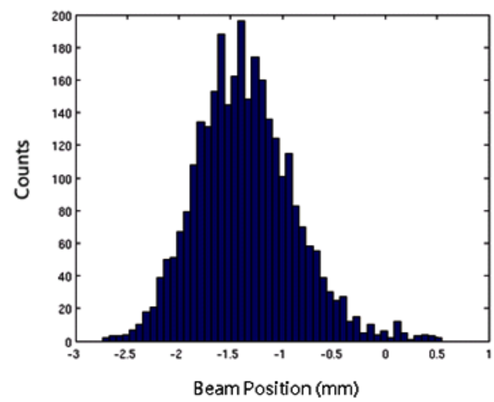

Figure 8: Measurement of beam-positions at the BAS3 in the PLS linac. See text for detailed descriptions.

In Fig. 9 we present the 8-hour energy stability which was also measured at the BAS3. The mean energies (obtained during every 10 seconds) were within +/- 5 MeV (0.2%). Please note that spikes in Fig. 9 are due to modulator trips and were excluded from the stability calculation.

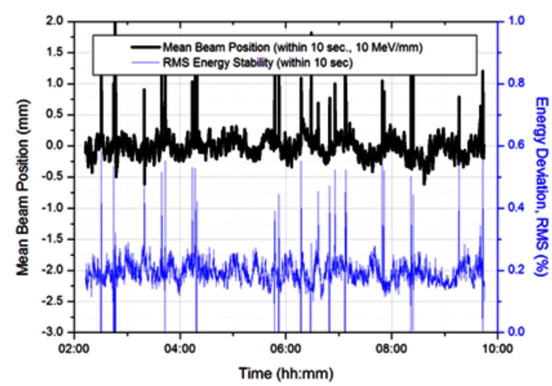

Figure 9: 8-hour Beam Position Stability at the BAS3. Mean Beam Positions over every 10 seconds were constant within +/- 0.5 mm (5 MeV) which translates into the pk-pk energy stability of < +/- 0.2%.

The energy stability achieved so far is believed to promise successful top-up operation. In the beginning of this September we have performed a test of top-up injections of which result shown in Fig. 10. For the 63-

hour top-up injections the linac energy was constant to within +/- 5 MeV (pk-pk). Operation statistics are summarized in Table 5.

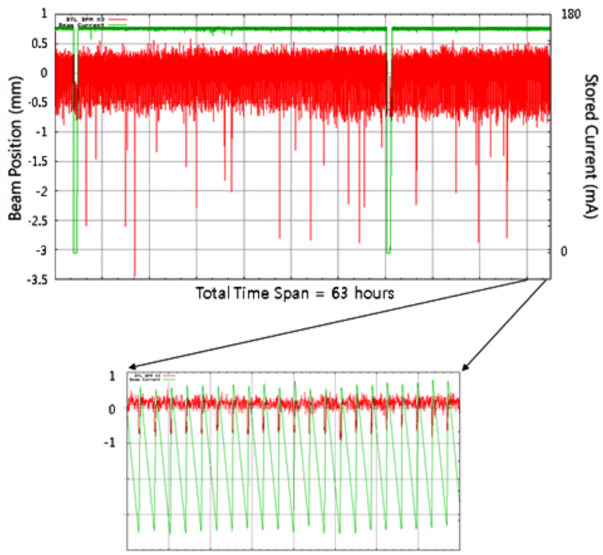

Figure 10: Profile of stored current (green lines) and beam position (red lines) at a dispersive section in linac-to-ring transfer line. Beam energy was constant to within +/- ~5 MeV for 63 hours. The two beam dumps were due to interlock actions from user beam-lines.

Table 5: Operation Statistics for the PLS Top-Up Test Injection Performed in the Beginning of September, 2010.

Total Operation Time [hr]	63
Total Down Time [hr]	2
Availability [%]	96.8
Total Number of Beam Dumps	2
Total Number of Linac Faults during injection	25
Average Time for an Injection [sec]	33
Linac Energy Variation (during Normal Operation)	pk-pk ~10 MeV (0.4%)

HIGH-BRIGHTNESS R&D

In order to be prepared for the linac-based light sources we have performed R&Ds on high-brightness electron source based on the photo-cathode RF gun. Starting from the BNL Gun-IV we have developed several guns with improved designs. The BNL Gun-IV was fabricated and tested in a test-stand [5]. The first improved gun is operating at the femto-second THz source facility in our lab. The second version with completely new design is being fabricated in house [6].

SUMMARY

- A major upgrade to the Pohang Light Source (PLS), the PLS-II project is well progressing.
- The PLS Linac is being upgraded to 3 GeV to be within existing building.
- In 2010 summer one acceleration unit (MK11) was successfully modified to double the RF power.
- Upgrades of cooling system and installation of digital LLRF system greatly improved the energy stability.
- Test of top-up operation for the PLS storage ring and linac proved excellent linac energy stability.
- High-brightness source R&Ds have been done to promise the bright future of the Pohang Accelerator Laboratory.

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