ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-THPRB117

# STABILITY AND RELIABILITY ISSUES OF PAL-XFEL MODULATOR*

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*Abstract*

The Pohang Accelerator Laboratory X-ray Free-Electron Laser (PAL-XFEL) employs 51 units of the pulse modulator in order to obtain the 10 GeV electron beam, which drive one X-band to linearize and 50 S-band klystrons. The PAL-XFEL requires very tight control of the klystron RF phase jitter 0.03-degree for S-band RF, 0.1-degree for X-band RF and the beam voltage stability of below 50 ppm. The RF phase jitter is directly related to the amplitude stability of modulator output pulses. There are several factors to satisfy the stability and reliability for the PAL-XFEL modulator. The largest sources of pulse-to-pulse instability are a current charging power supply (CCPS) for PFN charging, a thyratron switch, and a klystron focusing magnet power supply (MPS). In this paper, the operation and debugging results of those devices are described.

## INTRODUCTION

In order to obtain the electron beam energy of 10 GeV from PAL XFEL, We are expecting to employ 51 units of pulse modulators with matching klystrons. Among the 51 units, s-band types are fifty units, and x-band type is one. The requirements of a beam voltage stability and RF phase stability are 50 ppm (std), 0.03-degree (S-band), and 0.1-degree (X-band), respectively [1]. The high precision CCPS has been employed to meet the requirement for the modulator stability. It is very important to reduce the pulse-to-pulse instability in the PAL-XFEL facility. In order to fulfill these requirement:

- Improving the beam stability in the pulse modulator system.
- Modifying a thyratron snubber & grid circuitry, and ranging the thyratron reservoir voltage.
- Exchanging a SCR type of MPS with a FET type.

## CCPS

The modulator employees a high efficiency capacitor charging power supply that utilizes a high frequency, series resonant inverter topology. The power supply is specifically designed for constant current capacitor charging. It decides the rf phase and amplitude stability of a klystron output. Because a change in the output voltage of the CCPS is associated with the change of the klystron beam voltage, it varies the electron beam velocity in the drift tube of the klystron. With the help of the CCPS, the modulator system is naturally compact in spite of a 200 MW modulator power.

* Work supported by Ministry of Education, Science and Technology of the Korean Government.

### *Stability Measurement*

The experimental devices were set up to measure the modulator stability from PFN, beam voltage, and beam current as shown in Fig. 1. To obtain high precision of the voltage stability, we used a high voltage probe (VD60 Ross) which is very stable in temperature fluctuation. On the PFN, beam voltage, and beam current waveform, the zero offset is defined by a differential amplifier (DA1855A, Lecroy) setting a band width of 100 kHz. To display the histogram, an oscilloscope (DPO7104, Tektronix) equipped with a high resolution mode in an acquisition mode is used.

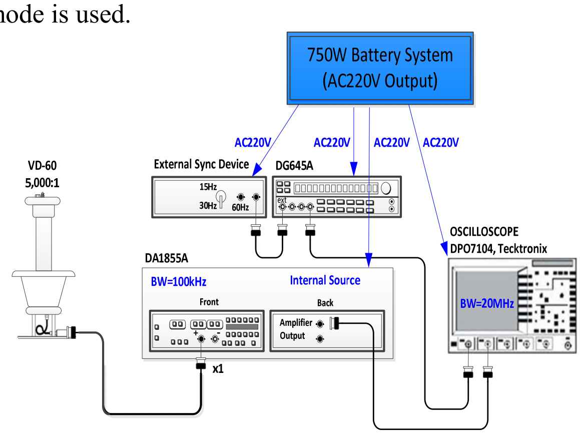


Figure 1: Test device for a stability measurement.

### *PFN Charging Voltage Waveform*

The capacitance of PFN in the 200 MW PAL-XFEL modulator is 1.4 µs, and the test operation condition is 42 kV at 60 Hz. The load is Toshiba s-band klystron (E37320). Figure 2 shows the expanded precision charging voltage waveform and control of voltage waveform in the regulation section of PFN. The size of the precision voltage in the regulation section is less than 2 V.

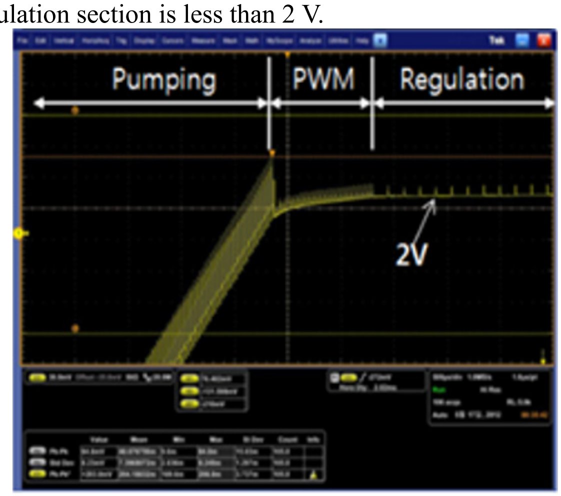


Figure 2: PFN charging voltage.

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### *Test Results*

In order to reduce switching noise from a thyratron switch in a modulator system, separated AC power and op-tic cables were used to block the switching noise while measuring the stability of PFN voltage. The measuring po-sition of PFN stability is 1 µs before switching of a thyra-tron. For each measurement it took about 3 minutes and performed 3 times after every 30 minutes waiting time. The stability of the PFN charging voltage was about 9 ppm shown in Fig. 3. In the same method as PFN measuring, the beam voltage stability was trying to do, and the meas-uring position of beam voltage stability was randomly se-lected from the flat-top, then set 5 ns for the time division. For each measurement it took about 3 minutes and per-formed 8 times for more accurate results after every 30 minutes waiting time. The stability of the beam voltage was about 29.6 ppm shown in Fig. 4. The slight devia-tion of the stability for each step was mainly due to tem-perature dependent time variation.

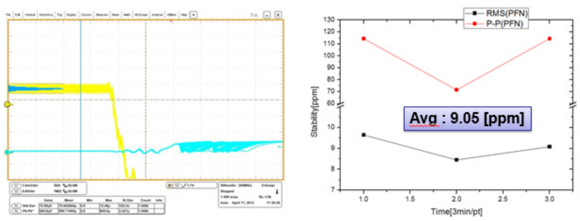


Figure 3: PFN voltage stability measurement.

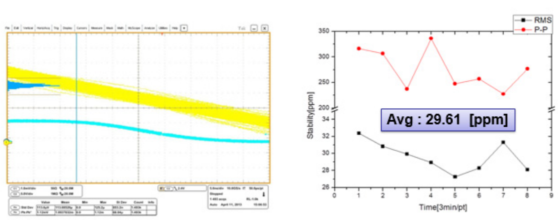


Figure 4: Beam voltage stability measurement.

## THYRATRON

We employ 51 units of E2V CX1836A thyratron and their trigger module in PAL-XFEL modulator system which consists of three control grids, two gap metal cera-mic, deuterium filled, and barium aluminate impregnated cathode. It is important to maintain stable $H_2$-gas pressure for a long term operatiom in order to achieve very stable beam stability from the klystron output.

### *Thyratron Performance*

The thyratron requires an optimum operation condition by maintaining a proper internal gas pressure. In order to obtain a stable high voltage operation with long life, the tube should be operated under optimum internal gas pres-sure. The CX1836A contains a barretter controlled reser-voir system which enables the optimization of the gas pres-sure in the tube.

Figure 5 shows the degradation in measuring the modu-lator beam current stability due to the time aging at thyra-tron run-times. The result is very important to understand that the largest source of pulse-to-pulse instability is com-ing from tubes in use for more than 15,000 hours. There-fore, we always have checked the stability of the beam cur-rent. In particular, the stability of the modulators installed on the front side (e-gun, L1, and L2 section) in the PAL-XFEL gallery is tightly controlled. We replace it with a new thyratron immediately if it exceeds 50 ppm by measuring at a modulator beam current.

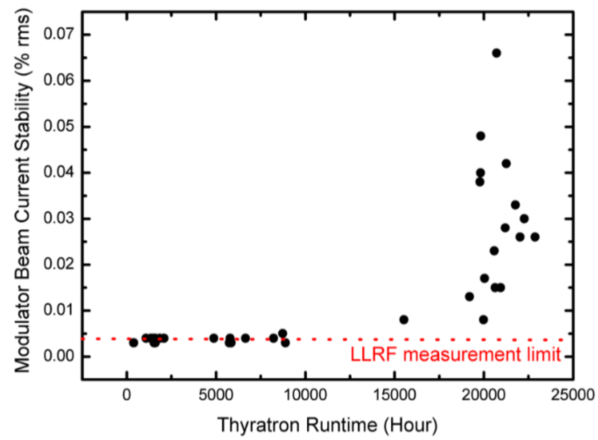


Figure 5: Modulator beam current stability according to the time aging at thyratron run-times.

### *Thyratron Reservoir Type*

The switching performance of the thyratron is very sen-sitive to the internal gas pressure. The gas pressure of 0.5 Torr is maintained by heating titanium hydride ($T_iH_2$) in porous nickel capsules (reservoir tank) loaded with several hundred tube-volumes of hydrogen. A high capacity reser-voir system minimizes gas pressure adjustments through-out tube life. Stable high-voltage operation requires each switch tube to be operated at the optimum pressure. Inten-sive checking and adjustment of the optimum ranging is a time-consuming part of modulator operation and mainte-nance in 51 units of PAL-XFEL modulator system.

### *RC Snubber*

The modulators at PAL-XFEL include a gradient grid network which has been a source of modulator reliability problems with breakdowns occurring approximately three or four times per month. We have found that increasing the power rating of the resistors from 13 to 55W and exchang-ing the capacitor model of 40DKT50 with that of FD-36AU have improved the fault situation.

### *Grid Circuitry*

We modified the grid circuitry to reduce fault problems from dynamic interlock in our modulator system. TVS components in the grid circuitry, 1.5KE400CA, were fail-ing frequently, so we introduced an LC filter as shown Fig. 6 for grid 1 only, 12.4 µH, 500 pF/40 kV, to protect the TVS from thyratron grid spike. The LC filter has reduced the amount of TVS damage effectively. All of grid boards

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in our modulator system have been modified to the same standard. No damage has been found in TVS components on the grid circuitry after modifying.

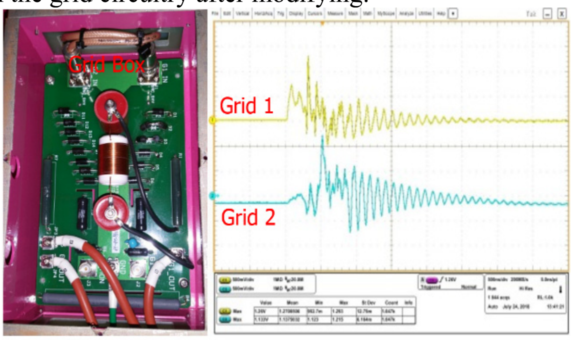


Figure 6: Grid box and grid views.

## MAGNET POWER SUPPLY

There are 50 modulators for the S-band klystrons, and one modulator for the X-band klystron that is used for linearizing the electron beam to obtain an electron beam energy of 10 GeV. The X-band cavity for linearization is placed right before the BC1. The PAL-XFEL LINAC is divided into 4 acceleration sections (L1, L2, L3, and L4), three bunch compressors (BC1, BC2, BC3), and a dogleg transport line to the undulators as shown in Fig. 7.

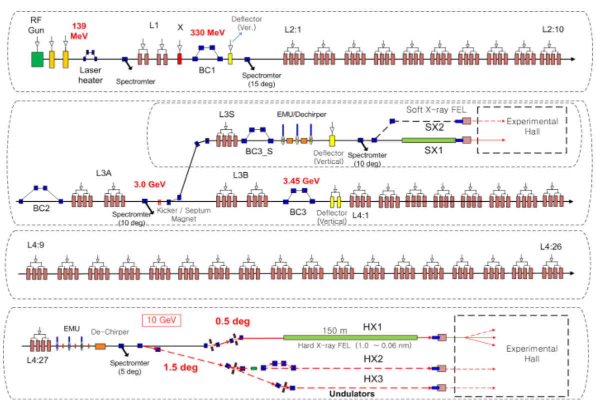


Figure 7: Schematic layout of PAL-XFEL.

The PAL-XFEL machine requires very stable modulator with the beam voltage stability of less than 50 ppm to get a 10 GeV electron beam with the energy spread of less than $5\times10^{-4}$ [2]. We found that the energy spread is highly dependent on the stability of the klystron magnet power supplies. In particular, the stability of them installed in the e-gun, L1, and L2 sections in PAL-XFEL gallery are very important.

We employ liquid cooled focusing electromagnet, VT-68915 for use with the E37320 high power pulse klystron. The electromagnet consists of several independent coils which provide the shapes field required to properly focus the klystron when energized with the proper current specified by the tube manufacturer.

### *Current Regulation for MPS*

In the operating instructions of Toshiba, a manufacture of E37308 klystron, the electromagnet power supply must current-regulated to better than 1%. Check the regulation before using the power supply. The resistance of the coils may increase between the application of the voltage and temperature stabilization. Apply the voltage to the electromagnet and adjust the current to within 1% of the prescribed value.

However, e-beam accelerating operation of PAL-XFEL has found that the stability of the electromagnet power supply is a very important factor affecting the instability of FEL operation. In case of modulators of the e-gun, L1, and L2 sections in PAL-XFEL gallery, the beam energy spread is highly dependent on stability of the MPS especially.

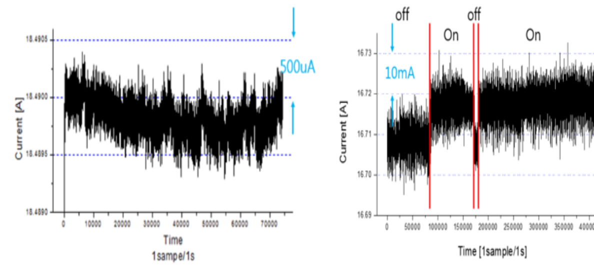


Figure 8: Current waveforms of MPS.

There are two types of MPS. One is FET and the other is SCR. Fig. 8 shows current waveforms of MPS. Left graph is measured from FET type MPS. Right graph is measured from SCR type MPS. The test results are listed below. The results of the stability from the FET type MPS and the SCR type MPS show that the former case was highly excellent. The FET type was installed at e-gun, L1, and L2 sections in PAL-XFEL gallery.

Table 1: Test Results

| | FET Type | SCR Type |
|---|---|---|
| $P_k$-$P_k$ | 0.75mA | 25mA |
| PPM | 37.5 | 1250 |

## CONCLUSION

In order to reduce the pulse-to pulse instability in the PAL-XFEL modulator system, we have fulfilled the requirements. The stability results of being measured at PFN and beam voltage were satisfying the requirement of < 20 ppm and < 50 ppm, respectively. When the thyratron performance deteriorated, the waveform of the beam current was continuously monitored to replace the new one to improve the beam stability in the pulse modulator system. Especially, the modulators at e-gun, L1, and L2 position have been specially managed because they have a great effect on the photon beam stabilization. We also modified a thyratron snubber and grid circuitry. No damage has been found in TVS components on the grid circuitry after trying to do. By installing the FET type MPS in the modulators at e-gun, L1, and L2 position, the photon beam energy spread was reduced almost twice.

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