

# OPERATIONAL CHARACTERISTICS OF PLS 2.5 GEV ELECTRON LINAC KLYSTRON-MODULATOR SYSTEMS

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## Abstract

The klystron-modulator(K&M) system of the Pohang Light Source(PLS) had been supplying high power microwaves for the acceleration of 2 GeV electron beams from 1994 to 2002. There are 12 sets of K&M systems to accelerate electron beams to 2 GeV nominal beam energy without operating one klystron-modulator, and the Energy Ramping System (ERS) was used to operate 2.5 GeV in storage ring. 12 sets of K&M system to accelerate electron beams to 2.5 GeV beam energy, however, have been running approximately 360 kV of the beam voltage respectively in order to inject 2.5 GeV beam energy to SR directly without ramping up to 2.5 GeV since October 2002. The PLS 2.5GeV linac employs 12 units of high power pulsed klystrons(80-MW) as the main RF sources. The matching modulators of 200-MW (400kV, 500A) can provide a flat-top pulse width of 4.4  $\mu$ sec with a maximum pulse repetition rate of 120-Hz at the full power level. The total accumulated high-voltage run-time of the oldest unit among 12 units has reached nearly 68,000 hours as of Dec. 2003, and the summation of all the units' high voltage run-time is approximately 820,000 hours. The overall system availability is well over 95%. There have been continuous efforts to improve the klystron-modulator system more stable and reliable. To improve self-diagnostic, operation, monitoring, and remote communication, we developed a new modulator controller based on an industrial PC platform in 2002. In this paper, we are able to review overall system performance of the high-power K&M system and the operational characteristics of the klystrons and thyatrons, and overall system's availability analysis from Jan. to Dec. 2003.

## INTRODUCTION

The Pohang Light Source is a third-generation synchrotron radiation facility. The klystron-modulator(K&M) system of the Pohang Light Source(PLS) had been supplying high power microwaves for the acceleration of 2 GeV electron beams from 1994 to 2002. It is mainly consisted of a 2.5 GeV full energy electron injection linac and a 2.5 GeV storage ring (SR) since October 2002. The 2.5 GeV full energy electron beam from the linac is transported through a beam transfer line (BTL) to the storage ring. Total 12 units of high power klystron-modulator (K&M) systems are under continuous operation in the PLS linac. The peak powers of the modulator and the klystron are 200 MW and 80 MW, respectively. The klystron output frequency is 2856 MHz. Each klystron output is compressed with a SLED

and supplied to four of three-meter long accelerating columns. The linac has been operated as a full energy injector for the PLS since December 1994. Annual operation hour of the K&M system is about 7,000 hours.

## KLYSTRON AND MODULATOR

To satisfy PLS linac design requirements, E3712 S-band klystron tube is selected as a main microwave source. The tube is manufactured by Toshiba in Japan. Total twelve klystrons are currently under operation, and eleven out of twelve klystrons are E3712. At the linac preinjector, a SLAC 5045 (65 MW peak) klystron is used. The modulator that mates with the klystron tube is manufactured by Pohang Accelerator Laboratory.

### Klystron

Operational parameters of the toshiba E3712 and SLAC 5045 klystron tube are listed in Table 1. The klystrons have two output ceramic windows to accommodate 80 MW and 60 MW peak power, respectively. The two outputs are combined after the window by a power combiner. The microwave power is compressed with a SLED to enhance accelerating field in the accelerating columns. Maximum accelerating field gradient of linac is 17 MV/m [2].

Table 1: Parameters of the E3712 and 5045 Klystron.

Description	Toshiba E3712	SLAC 5045
Frequency	2,856 MHz	2,856 MHz
Pulse-width	4 $\mu$ s	3.5 $\mu$ s
Repetition Rate	60 Hz Max.	180 Hz Max.
Beam Voltage	400 kV	350 kV
Beam Current	500 A	420 A
$\mu$ -perveance	2.0	2.0
RF Output Power	84 MW Peak	60 MW Peak
Drive Power	500 W Max	600 W Max
Gain	53 dB Max	49 dB Max
Efficiency	42 %	40 %
Focusing	Electromagnet	Electromagnet

### Modulator

Specifications of the modulator are listed in Table 2. Maximum repetition rate of the modulator is 180 Hz as given in Table 1. However, the normal operating rate is 30 Hz. The injection rate of the electron beam to the PLS storage ring is 10 Hz. Fig. 1 shows a simplified modulator circuit. The modulator can be divided into four major

sections: a charging section, a discharging section, a pulse transformer tank, and a klystron load. In the charging section, a SCR AC-AC voltage regulator controls primary 3-phase 480 V AC power. The voltage regulator receives feedback signals from the primary AC voltage and the high voltage DC (HVDC) detector as shown in Fig. 1.

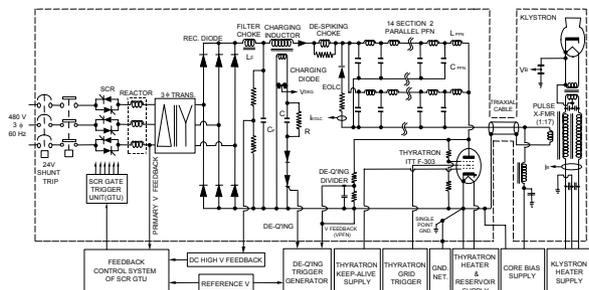


Figure 1: Schematic circuit diagram of the modulator.

Table 2: Modulator Specification.

Description	Parameter
Peak Power	200 MW max.
Average Power	289 kW max 48 kW normal
Repetition Rate (PRR)	180 Hz max. 30 Hz normal
Peak Output Voltage	400 kV
ESW	7.5 μs
Flat-top Width (<±0.5%)	4.4 μs
Charging Time	5.76 ms

The closed loop control of the AC-AC voltage regulator ensures stable HVDC output. The maximum HVDC is 25 kV. For the system and personal safety, the interlock has the static and the dynamic mode. The static mode has the interlock of doors, ground hooks, heater PS, flow and temperature of cooling, over voltage and current, etc. The dynamic mode has the analog signal from the vacuum system and the digital signal of SCR ac over current. The pulse forming network (PFN) is resonantly charged from the HVDC filter capacitor through the charging inductor and diode. Pulse-to-pulse beam voltage regulation is less than ± 0.5%. Two parallel, fourteen section, type-E Guillemin networks [3] are used for the PFN. The PFN impedance is about 2.8 Ω. Each PFN capacitor has a fixed capacitance of 50 nF, and each PFN inductor can be varied manually up to 4.5 μH. By adjusting inductance of each PFN section, we can precisely tune the flattop of the modulator output voltage pulse. The end of line clipper (EOLC) removes excessive negative voltage developed after discharge on the PFN capacitors as well as the thyatron. Three thyatron types have been tested and installed in the modulator: ITT F-303, EEV CX-1836A, and LITTON L-4888. All three types has similar electrical specification, and the ITT F-303 specification is given in Table 3.

Table 3: 200 MW Thyatron (ITT F-303) Specification.

Description	ITT Spec.	PLS Spec.	
		30 Hz	180Hz
Peak Power (MW)	200	202	202
Ave. Power	200	45.5	273
Peak Anode V (kV), $E_{py}$	50	47	47
Peak Anode I (kA), $i_b$	15	8.6	8.6
$Di_b/dt$ (kA/μs)	50	10.75	10.75
Ave. Anode I (ADC)	8 in Air 12 in oil	3.87	11.61
$E_{py} \times i_b \times PRR (x 10^9)$	300	24.3	72.8
$E_{py} \times di_b/dtxPRR (x 10^{15})$	---	30	91

Two triaxial cables in parallel are used to make electrical connections between the PFN and the pulse transformer. The pulse transformer has 1:17 turn ratio.

Components in the pulse transformer tank are immersed in high voltage insulating mineral oil. The klystron sits on the pulse tank top cover and is connected to the high voltage output of the pulse transformer. The klystron impedance at the primary of the pulse transformer is 2.8 Ω that matches with the PFN impedance. During fine-tuning of the PFN impedance, we intentionally produced about 5% positive mismatch to extend switch lifetime by reducing the thyatron anode dissipation [4, 5].

### Operation Status

The current status of the klystron tube is given in Table 4. Since the installation of the linac in 1993, nine klystrons had been failed and replaced. The average heater run time of the failure klystron is about 50,700 hr. Those were the ones in station numbers 1, 2, 6, 7, 8, 9, 10, 11, and 12.

Table 4: Status of the Klystron (As of Dec. 24, 2003)

Mod. No	Tube Type	Tube Serial No.	Heater Time(Hr)*	Replacement
M01	SLAC5045	622A	3,799	2003-05-21
M02	E3712	21011PLS	60,170	1995-08-12
M03	E3712	PLS002	76,032	1993-05-01
M04	E3712	74003PLS	75,910	1993-06-01
M05	E3712	89004PLS	75,180	1993-07-01
M06	E3712	14012PLS	47,963	1997-02-25
M07	E3712	77016PLS	2,409	2003-08-04
M08	E3712	82013PLS	47,318	1997-03-28
M09	E3712	96014PLS	5,449	2003-03-07
M10	E3712	40018PLS	1,543	2003-10-17
M11	E3712	65017PLS	2,411	2003-08-20
M12	E3712	65008PLS/R	14,435	2001-12-26

The numbers given in parenthesis at the installed date column are the accumulated high voltage run-time of the failed tubes at the time of replacement. The klystron that has the longest operation is the one in station number 3, and its high voltage run time reaches more than 68,000 hours as of December 2003.

The current status of the thyatron tube is given. As mentioned before, two types of thyatrons are placed in the modulator. The high voltage runtime is the total accumulated hour, and it does not imply the installed thyatron run hour. A thyatron that has the longest run-hour is the one in station 4. It reaches more than 76,000 hours.

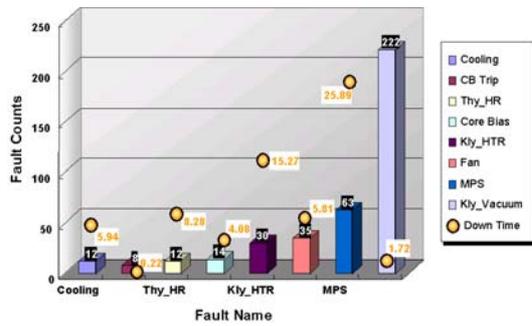


Figure 2: Static fault analysis of the klystron and modulator system (January to December 24, 2003)

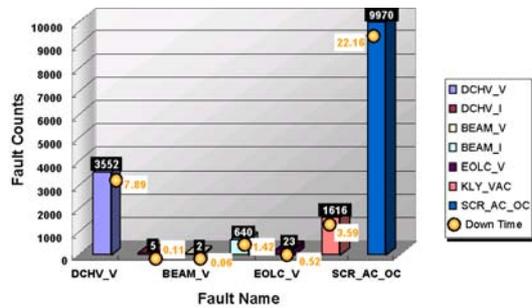


Figure 3: Dynamic fault analysis of the klystron and modulator system (January to December 24, 2003)

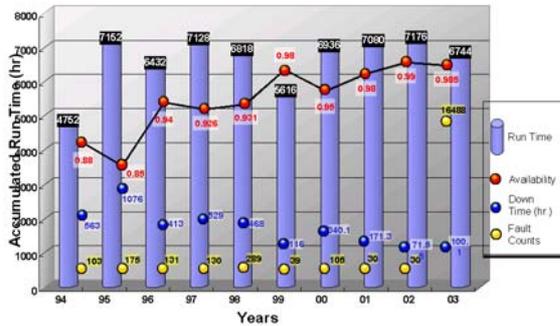


Figure 4: Availability, down time, and fault count of modulator during 1994 to 2003.

The static and dynamic fault analysis of the K&M system during the period of January to December of 2003 is shown in Fig. 2 and Fig. 3. From Fig. 2, the klystron vacuum has the highest static fault count because the heater of the klystron is long operation.

The vacuum fault of the klystron often occurred during the condition of the high voltage. From the Table 8, we can see the availability almost same in 2003 compared to the previous years. At 2003, the system availability was about 98.5 %. The availability, down time, and fault count of modulator is shown in Fig. 4 during 1994 to

2003. The reduction of availability has been caused by the added dynamic fault. In Fig. 3, The DCHV over-voltage and SCR ac over-current was caused by thyatron misfire due to misleading timing signals and electronic circuit malfunction due to electrical noises. We are trying to reduce the system failure dynamic and static count further.

## SUMMARY

The K&M system is a key unit in linac facilities. PLS linac has 12 units of K&M system. The klystron is the S-band E3712 that is manufactured by Toshiba in Japan. It has about 80 MW peak power. The modulator is designed and constructed in PAL. The modulator has 200 MW peak power. The K&M system started its full operation in 1994. Among the twelve K&M units, one with the longest operation hour has accumulated over 73,000 hours operation time as of December 2003. Fault and availability analysis of the K&M system show that the system is running very stable and reliable, and the performance of the system has been continuously improved. To improve self-diagnostic, operation, monitoring, and remote communication, we developed a new modulator controller based on an industrial PC platform in 2002. We reviewed overall system performance of the high-power K&M system and the operational characteristics of the klystrons and thyatrons, and overall system's availability analysis from 1994 to December 2003.

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