OPERATIONAL ANALYSIS OF PLS 2.5-GEV ELECTRON LINAC KLYSTRON-MODULATOR SYSTEM*

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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. The PLS 2.5GeV linac employs 12 units of high power pulsed klystrons(80-MW) as the main RF sources since October 2002. The matching modulators of 200-MW (400kV, 500A) can provide a flat-top pulse width of 4.4 μsec 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. The overall system availability is well over 95%. 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 thyratrons, and overall system's availability analysis from Jan. to Dec. 2003.

INTRODUCTION

The Pohang Light Source(PLS) is a third-generation synchrotron radiation facility. The klystron-modulator(K&M) system of the Pohang Light Source had been supplying high power microwaves for the acceleration of 2 GeV electron beams from 1994 to 2002. It mainly consists 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 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.

We 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.

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 a Toshiba in Japan. Total twelve klystrons are currently under operation, and eleven out of twelve klystrons are E3712. At the linac pre-injector, a SLAC 5045 (65 MW peak) klystron is used. The modulator matched with the klystron tube is manufactured by Pohang Light Source.

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 μs	3.5 μs
Repetition Rate	60 Hz Max.	180 Hz Max.
Beam Voltage	400 kV	350 kV
Beam Current	500 A	420 A
μ-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.

Table 2. Modulator Specification.

Description	*Parameter*
Peak Power	200 MW max.
Average Power	289 kWmax, 48 kWnormal
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

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. 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.The

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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. The De-Q'ing circuit is installed at the secondary of the charging inductor to regulate the PFN charging voltage. Pulse-to-pulse beam voltage regulation is less than ± 0.5%. Two parallel, fourteen sections, 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.

Table 3. 200 MW Thyratron (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	3.87	11.61
	12 in oil	--	--
E_{py} x i_b x PRR (x 10^9)	300	24.3	72.8
E_{py} x di_b/dt x PRR (x 10^{15})	---	30	91

The end of line clipper (EOLC) removes excessive negative voltage developed after discharge on the PFN capacitors as well as the thyratron. Three thyratron types have been tested and installed in the modulator: ITT F-303, and LITTON L-4888. All three types have similar electrical specification, and the ITT F-303 specification is given in Table 3. Forced air-cooling is used for the thyratron. 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 matched 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 thyratron anode dissipation [4, 5, 6].

Operation Status

The current status of the klystron tube is given in Table 4.

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

Mod. No	*Tube Type*	*Tube Serial No.*	*HeaterTime(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

Since the installation of the linac in 1993, nine klystrons had been failed and replaced. The failure status of the klystrons and average heater run time of the failure klystron is about 50,700 hr. 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 failure status of nine failed klystrons was all different kind. The klystron in the station 6 showed a bad internal vacuum and caused frequent internal arcing. Heater shortage occurred in the station 8 klystron. And others are heater out of run time.

In Table 5, current status of the thyratron tube is given. As mentioned before, two types of thyratrons are placed in the modulator as listed in Table 5. A thyratron that has the longest run-hour is the one in station 4. It reaches more than 76,000 hours. The thyratron failure occurs more often than the klystrons. The main causes of thyratron replacement can be summarized by three problems that are high switching jitter, out of reservoir ranging control, and internal electrode or grid short.

Table 5. Status of the thyratron (As of Dec. 24, 2003)

Mod. No	Thyratron Tube		Heater	Reservoir	Run Time[Hr]	DC H.V	
	Model	Serial No	Vh[v]	Vr[V]		[KV]	R.T[Hr]
M01	New F-303	834	6.37	3.91	12,324	17.8	68,840
M02	L-4888	100032	7.17	4.74	50,582	18.0	72,845
M03	F-303	828	6.62	3.54	28,413	18.5	71,780
M04	F-303	107	6.32	4.00	76,366	18.0	71,266
M05	F-303	832	6.31	4.41	23,910	17.3	70,493
M06	L-4888	100045	7.18	5.93	66,032	18.3	70,368
M07	New F-303	877	6.6	4.48	16,052	18.3	70,868
M08	F-303	833	6.37	4.13	19,876	18.4	71,635
M09	F-303	879	6.19	3.96	267	17.6	70,525
M10	F-303	878	6.41	3.57	5,000	18.2	68,888
M11	New F-303	831	6.37	4.61	24,718	18.1	69,828
M12	F-303	138	6.44	5.51	37,548	17.2	45,399
test linac	CX1836A	1436	6.31	6.31	7,380	16.1	16,950

Fault and Availability Analysis of the Modulator

Modulator controllers were developed for Linac klystron and modulator system of the PLS. This controller can check up operation data of the K&M system in real time. The modulator controller mainly consisted of an interlock signal conditioning module, a fast pulse signal-conditioning module, and the main PC platform. There are 72 interlock points including dynamic(9^{th} interlock points), static(48^{th}), trigger(2), and other interlocks(13^{th}) for K&M system.

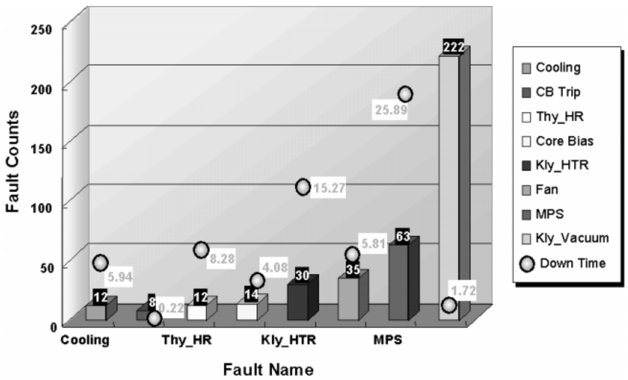

Figure 1. Static fault analysis of the klystron and modulator system (from January to December 24, 2003)

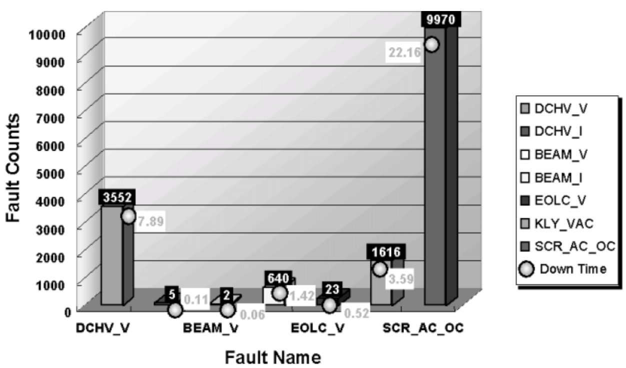

Figure 2. Dynamic fault analysis of the klystron and modulator system (from January to December 24, 2003)

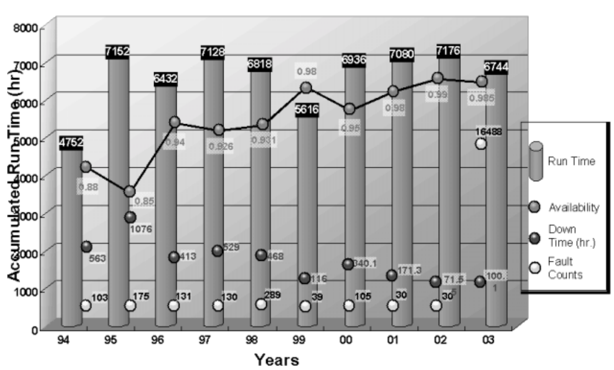

Figure 3. Availability, down time, and fault count of modulator during 1994 to 2003.

Fig. 1 and Fig. 2 show the static and dynamic fault analysis of the K&M system from January to December. From Fig. 1, the klystron vacuum has the highest static fault count because the heater of the klystron has used longer operation since setup. From Fig. 2, the SCR AC over-current and DCHV over-voltage have the dynamic fault counts because of self-fire of the thyratron or misleading timing signals and electronic circuit breakdown due to electrical noises. Fig. 3 shows the availability analysis of the system has been listed since its installation. Because the vacuum fault of the klystron often occurred during the condition of the high voltage, the system availability was about 95 % in 2000. We can see the availability almost same in 2003 compared to the previous years. In 2003, the system availability was about 98.5 %. The reduction of availability has been caused by the added dynamic fault at 2003. 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, thus it is important for us to keep the system stable. To get the stability of beam energy, the energy ramping system no longer used to operate 2.5 GeV in storage ring and 2.5 GeV beam energy is supplied to to SR directly without ramping up to 2.5 GeV since October 2002. To improve self-diagnostic, operation, monitoring, and remote communication, we developed new modulator controllers based on an industrial PC platform. Thanks to the modulator controller, all of the operation data of the K&M system can be acquired and saved in real time. 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. We also reviewed overall system performance of the high-power K&M system and the operational characteristics of the klystrons and thyratrons, and overall system's availability analysis from 1994 to December 2003. In 2003, the system availability was about 98.5 %.

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