KLYSTRON-MODULATOR SYSTEM PERFORMANCE IN PLS 2-GEV ELECTRON LINAC

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Abstract

Total 12 units of high power klystron-modulator systems are under continuous operation in the Pohang Light Source (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 [1] and supplied to four of three-meter long accelerating columns. Final electron energy of PLS linac is 2 GeV. The linac has been operated as a full energy injector for the PLS since December 1994. Annual operation hour of the system is about 5000 hours. Since the commissioning of the PLS linac, the total high voltage run time of an oldest unit among the 12 systems has been accumulated over 42,000-hours as of May 1999, and summation of all the units' high voltage run time is approximately 458,000 hours. The overall system availability is well over 90%. To enhance the klystron lifetime, a 'cathode back-heating' operation mode was adopted from May 1999. In this paper, we review overall system performance of the klystron-modulator system. The operational status of the klystrons and thyratrons, and the overall system availability statistics for the period of 1994 to May 1999 are also discussed.

I. INTRODUCTION

The Pohang Light Source (PLS) is a third-generation synchrotron radiation facility. The PLS is mainly consisted of a 2 GeV full energy electron injection linac and a 2.0 GeV storage ring (SR). The 2 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 5000 hours.

II. 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 the twelve klystrons are E3712. At the linac preinjector, a SLAC 5045 (60 MW peak) klystron is used. The modulator that mates with the klystron tube is manufactured in Pohang Accelerator Laboratory (PAL).

A. *Klystron*

Operational parameters of the E3712 klystron tube are listed in Table 1. The klystron has two output ceramic windows to accommodate 80 MW peak power. 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]. Fig. 1 shows the output power and efficiency of the E3712 klystron as the beam voltage varies. In Fig. 2, the transfer characteristic of the E3712 klystron is shown.

Table 1. Parameters of the E3712 Klystron.

Description	Parameter
Frequency	2,856 MHz
Pulse-width	4 μs
Repetition Rate	60 Hz Max.
Beam Voltage	400 kV
Beam Current	500 A
μ-perveance	2.0
RF Output Power	84 MW Peak
Drive Power	500 W Max
Gain	53 dB Max
Efficiency	42 %
Focusing	Electromagnet

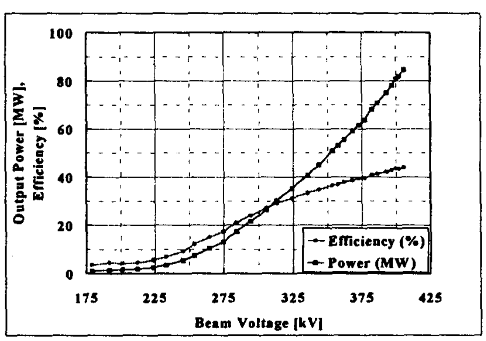

Figure 1. E3712 klystron beam voltage versus output power.

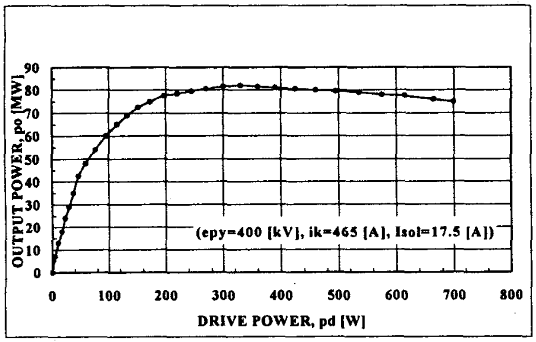

Figure 2. Transfer characteristic of the E3712 klystron.

B. 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. 3 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 current detectors, and also from the high voltage DC (HVDC) detector as shown in Fig. 1. The closed loop control of the AC-AC voltage regulator ensures stable HVDC output. The maximum HVDC is 25 kV. 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 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) shown in Fig. 1 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, 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. 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 seen 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 thyratron anode dissipation [4, 5].

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

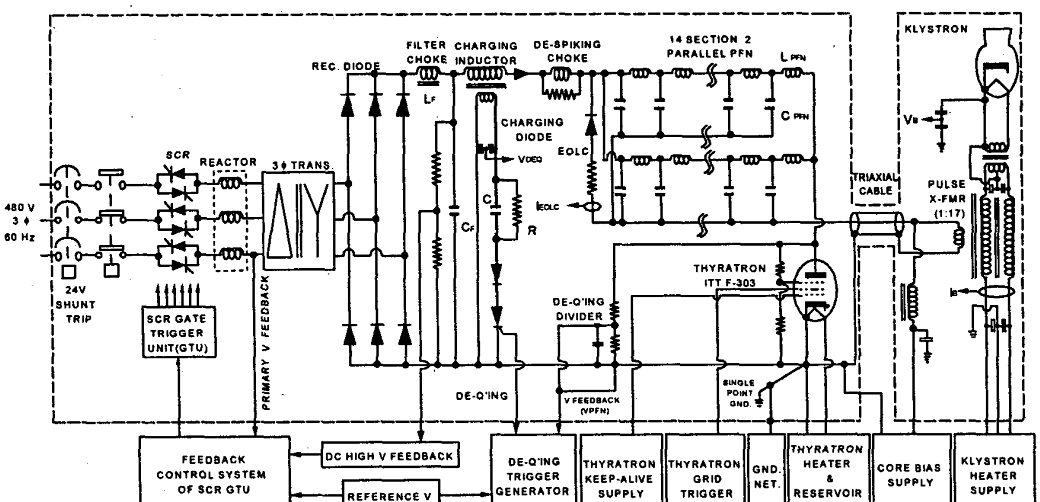

Figure 3. Schematic circuit diagram of the modulator.

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

Description	ITT Spec.	PLS Spec.	
		30 Hz	180 Hz
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	--	--
$E_{py} \times i_b \times PRR$ ($\times 10^9$)	300	24.3	72.8
$E_{py} \times di_b/dt \times PRR$ ($\times 10^{15}$)	---	30	91

C. Operation Status

Current status of the klystron tube is given in Table 4. Since the installation of the linac in 1993, three klystrons had been failed and replaced. Those were the ones in station numbers 2, 6, and 8 as shown in Table 4. The numbers given in parenthesis at the installed date column are the accumulated high voltage run time of the failed tubes at the time replacement. The klystron that has the longest operation is one in station number 3, and its high voltage run time reaches more than 42,000 hours as of May 1999. Failure modes for the three failed klystrons were all different. The klystron in the station 2 had an electrode damage due to a focusing electromagnet shortage. The klystron in the station 6 showed bad internal vacuum and caused frequent internal arcing. Heater shortage occurred in the station 8 klystron. The warranted lifetime of E3712 is 10,000 hours. However, the data listed in Table 4 clearly show that the real lifetime is much longer than the warranted lifetime. The klystron is very costly, and replacement of the klystron requires long shutdown time. Therefore, prediction of the klystron lifetime is important for the linac budget and maintenance schedule. But the data collected in the PLS linac are not enough to get a statistical lifetime which can be used for a reference. Furthermore, collection of the data from other facilities worldwide is impossible because the PLS linac is the first such facility to require 80 MW peak power which is the E3712 output. In our plan, we are preparing spare klystrons expecting that the average lifetime will exceed over 45,000 hours. In an effort to extend the klystron lifetime, we have recently developed a new operation mode so called 'cathode back-heating'. In this operation mode, the klystron heater current is reduced from about 4.9 A (~450 W) to 4.2 A (300 W). Each current corresponds to 920°C and 770°C cathode temperature, respectively. The E3712 klystron uses a Sc type cathode. The 'cathode back-heating' mode is possible when the klystron is in long stand-by state. Other than short injection time of the electron beams from the linac to the PLS storage ring, the klystron is in stand-by state. By reducing the klystron cathode temperature to 770°C, Ba evaporation rate reduces about 92.3 % compared to the case with 920°C temperature [6]. Therefore, high voltage application to suppress the Ba coating on insulators and electrodes is not necessary. The lower the cathode temperature, the lower the Ba evaporation rate. However, a low temperature causes higher thermal stress to the filament. The cathode temperature of 770°C is a recommended value from the manufacturer to compromise the thermal stress and the Ba evaporation rate. To recover the klystron in normal operation, the heater power is increased to its normal value (~450 W) and more than 30 minutes time delay is maintained before the application of high voltage.

Table 4. Status of the Klystron (As of May 29, 1999)

MK No.	Klystron Model	HV Run(hr)	Heater Run(hr)	Installed Date
1	SLAC 5045 (S/N:511A)	39,375	43,929	93.07
2	E3712 (S/N:21011PLS)	42,975	28,041	95.08(18833)
3	E3712 (S/N:PLS002)	42,100	43,893	93.05
4	E3712 (S/N:74003PLS)	41,461	43,797	93.05
5	E3712 (S/N:89004PLS)	40,530	43,093	93.06
6	E3712 (S/N:14012PLS)	40,612	15,781	97.02(26772)
7	E3712 (S/N:65007PLS)	39,625	41,964	93.09
8	E3712 (S/N:82013PLS)	40,513	15,235	97.03(27290)
9	E3712 (S/N:41009PLS)	39,089	41,640	93.10
10	E3712 (S/N:98010PLS)	39,299	41,499	93.11
11	E3712 (S/N:77006PLS)	38,675	41,760	93.11
12	E3712 (S/N:93015PLS)	14,293	10,444	97.10

In Table 5, current status of the thyratron tube is given. As mentioned before, three types of thyratron are placed in the modulator as listed in Table 5. The high voltage run-hour in Table 5 is the total accumulated hour, and it does not imply the installed thyratron run hour. A thyratron that has the longest run-hour is the one in station 4. It reaches more than 41,000 hours. The thyratron failure occurs more often than the klystrons. The main causes of thyratron replacement can be summarized by three problems: high switching jitter, out of reservoir ranging control, and internal electrode or grid short.

Table 5. Status of the Thyratron (As of May 29, 1999)

MK No.	Thyratron Model	HV Run(hr)	Heater Run(hr)	Replaced Date
1	ITT F-303(S/N:136)	38,375	10,453	97.11
2	LITTON L-4888(S/N:100032)	42,975	33,447(15261)	96.11
3	EEV CX-1836A(S/N:1347)	42,100	5,345	98.08
4	ITT F-303(S/N:107)	41,461	44,015	93.07
5	EEV CX-1836A(S/N:1410)	40,530	1,888	99.03
6	LITTON L-4888(S/N:100045)	40,612	33,628	94.12
7	ITT F-303(S/N:137)	39,625	10,371	97.11
8	ITT F-303(S/N:112)	40,513	42,620	93.11
9	ITT F-303(S/N:105)	39,089	42,219	93.12
10	ITT F-303(S/N:114R)	39,299	28,868	95.06
11	ITT F-303(S/N:135)	38,675	13,438	97.06
12	ITT F-303(S/N:138)	14,293	4,678	98.09

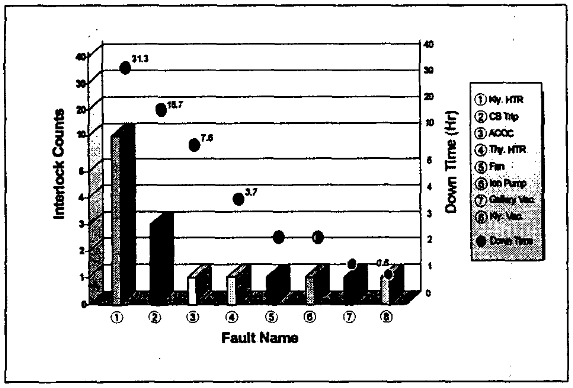

Figure 4. Fault analysis of the klystron and modulator system (Jan. 25, 1999 – Man 29, 1999)

Table 6. Availability analysis of the klystron-modulator. (As of May 29, 1999)

As of May 29, 1999

Total No. of Modulators	11	11	11	11	12	12
Operation Time (hr)	4,752	7,162	6,432	7,128	6,816	2,880
Total Failure Counts	103	175	131	130	289	19
Total Down Time (hr)	563	1,075.8	413	529	468	64
System MTBF (hr)	28	41	49	55	24	151
MTTR (hr/failure)	5.46	6.15	3.15	4.07	1.62	3.37
Availability (%)	81	85	94	93	93	97.7

A(%) = 1 - FR x MTTR, FR : Failure Rate (No. of Faults / Run Time), MTTR (Mean Time to Repair)

The fault analysis of the K&M system during the period of January to May of 1999 is shown in Fig. 4. In Table 6, the availability analysis of the system is listed since its installation. From Fig. 4, the klystron heater power supply has the highest fault count and the longest down time. However, the total down time is not significantly large compared to the total system operation time. From Table 6, the comparison result can be recognized. The system availability in 1999 is 97.7 %. This inversely implies that the down time is 2.3 % of the total operation hour. We are trying to reduce the system failure count further. From the Table 6, the availability dramatically improves in 1999 compared to the previous years. Before 1999, the system availability was about 93 %. The improvement has been achieved by reducing over-current trip count (CB Trip) of the modulator. The over-current was caused by thyratron misfire due to misleading timing signals and electronic circuit malfunction due to electrical noises. Fig. 5 shows typical waveforms of the beam voltage output, the klystron microwave output, and the SLED output. Energy gain of the electron beam from the SLED is about 1.5. In normal operation mode, the klystron output power ranges from 60 to 65 MW.

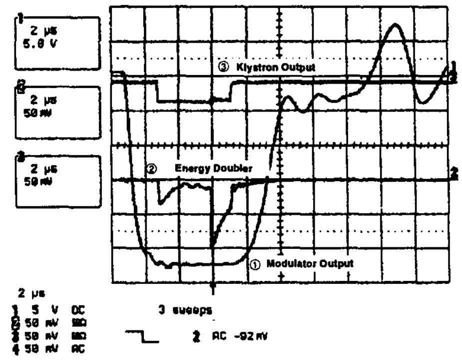

Figure 5. Typical waveforms of the modulator beam voltage (345 kV peak), the klystron output (53 MW peak), and the SLED output.

III. 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 42,000 hours operation time as of May 1999. Fault as well as availability analysis of the K&M system show that the system is running very stable and reliable, and performance of the system has been continuously improved. To increase the klystron lifetime, a new operation mode, 'cathode back heating', was newly developed. The 'cathode back-heating' mode dramatically reduced Ba evaporation rate from the klystron cathode.

IV. REFERENCES

[1] Z. D. Farkas et al., "SLED: A Method for Doubling SLAC's Energy," Proc. Of 9th Int. Conf. On High Energy Accelerators, SLAC, 1974, p. 576.

[2] W. Namkung et al., " PLS 2 GeV Linac," Proc. of 17th Int'l Linac Conf., Tsukuba, Japan, Aug. 21-26, 1994, pp. 14-16.

[3] G. N. Glasoe and J. V. Lebacqz, *Pulse Generators*, McGraw-Hill, 1948, Chapter 6.

[4] S. H. Nam, J. S. Oh, M. H. Cho, and W. Namkung, "Prototype Pulse Modulator for High Power Klystron in PLS Linac," IEEE Conf. Records of the 20the Power Modulator Symp., Myrtle Beach, SC, 1992, pp. 96-99.

[5] R. B. Neal, ed., *The Stanford Two-Mile Accelerator*, Q. A. Benjamin, New York, 1968.

[6] K. Kabayashi, et al., "Ba evaporation of Ir coated cathode impregnated cathode," Vacuum (Japanese), Vol. 29 (No. 3), 1989, pp 305-307.