OPERATIONAL CHARACTERISTICS AND AVAILABILITY OF KLYSTRON-MODULATOR SYSTEM FOR 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 6,000-hours. Since the commissioning of the PLS linac, the high voltage run time of an oldest unit among the 12 systems has been accumulated over 60,000-hours as of December 2001, and summation of all the units' high voltage run time is approximately 668,000 hours. The overall system availability is well over 90%. In this paper, we review overall system performance of the klystron-modulator systems. The operational status of the klystrons and thyratrons, and the overall system availability statistics for the period of 1994 to December 2001 are also discussed.

1 INTRODUCTION

The Pohang Light Source is a third-generation synchrotron radiation facility. It 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 6,000 hours.

2 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 (60 MW peak) klystron is used. The modulator that mates with the klystron tube is manufactured in Pohang Accelerator Laboratory.

2.1 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

2.2 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. 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.

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 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. 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.

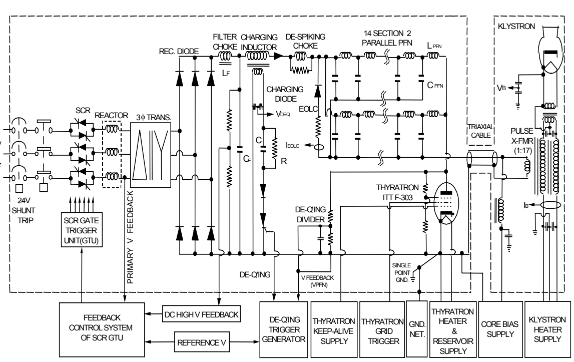

Figure 2. Schematic circuit diagram of the modulator.

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].

2.3 Operation Status

The current status of the klystron tube is given in Table 3. Since the installation of the linac in 1993, fore klystrons had been failed and replaced.

Table 3. Status of the Klystron (As of Dec. 26, 2001)

MK No.	Klystron Model	HV Run(hr)	Heater Run(hr)	Installed Date
1	SLAC 5045 (S/N:511A)	55,751	61,815	93.07
2	E3712 (S/N:21011PLS)	60,646	45,949	95.08(18833)
3	E3712 (S/N:PLS002)	59,594	61,766	93.05
4	E3712 (S/N:74003PLS)	59,086	61,683	93.05
5	E3712 (S/N:89004PLS)	57,909	60,952	93.06
6	E3712 (S/N:14012PLS)	58,166	33,724	97.02(26772)
7	E3712 (S/N:65007PLS)	57,083	59,774	93.09
8	E3712 (S/N:82013PLS)	57,702	33,115	97.03(27290)
9	E3712 (S/N:41009PLS)	56,506	59,520	93.10
10	E3712 (S/N:98010PLS)	56,857	59,417	93.11
11	E3712 (S/N:77006PLS)	55,970	59,634	93.11
12	E3712 (S/N:65008PLS/R)	31,308	0	01.12(28463)

Table 4. shows the failure status of the klystrons. Those were the ones in station numbers 2, 6, 8, and 12 as shown in Table 3. 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 60,000 hours as of December 2001. Failure modes for the fore failed klystrons were all different kind as shown in Table 4. 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.

Table 4. Failure Status of the klystron.

MK No.(Model #)	HV Run(hr)	Heater Run(hr)	Installed Date	Problems
2(S/N:21011PLS)	16,183	18,833	95.08	Mag. Coil short, Arc(13 kV)
6(S/N:14012PLS)	25,381	26,772	97.02	Kly. Arc (14 kV), Mag. Noise
8(S/N:82013PLS)	25,408	27,290	97.03	Heater internal short
12(S/N:93015PLS)	31,340	28,436	97.03	Cavity Damage

The klystron in the station 12 had a cavity damage due to spot heating. The warranted lifetime of E3712 is 10,000 hours. However, the data listed in Table 3 clearly show that the real lifetime is much longer than the warranted lifetime. The klystron is very costly, and replacement of the klystron requires for a long shutdown time. Therefore, prediction of the klystron lifetime is important for the Linac budget and maintenance schedule.

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 62,000 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 Dec. 26, 2001)

MK No.	Thyratron Model	HV Run(hr)	Heater Run(hr)	Replaced Date
1	ITT F-303(S/N:136)	55,751	28,537	97.11
2	LITTON L-4888(S/N:100032)	60,646	51,491(15261)	96.11
3	ITT F-303(S/N:828)	59,594	14,035	99.12
4	ITT F-303(S/N:107)	59,086	62,017	93.07
5	ITT F-303(S/N:832)	57,909	9,543	00.07
6	LITTON L-4888(S/N:100045)	58,166	51,677	94.12
7	ITT F-303(S/N:877)	57,083	1,708	01.09
8	ITT F-303(S/N:833)	57,702	5,534	01.03
9	ITT F-303(S/N:105)	56,506	60,257	93.12
10	ITT F-303(S/N:114R)	56,857	46,939	95.06
11	ITT F-303(S/N:831)	55,970	10,281	00.06
12	ITT F-303(S/N:138)	31,308	22,812	98.09

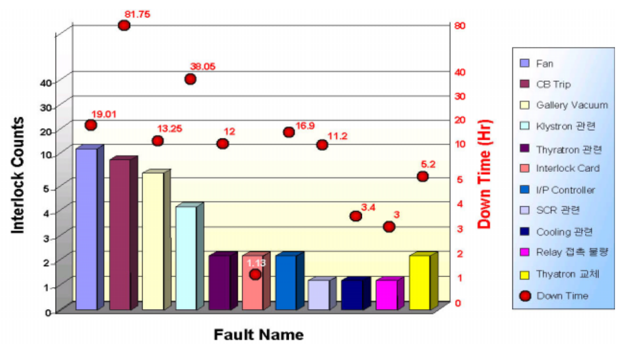

Figure 2. Fault analysis of the klystron and modulator system (Jan. 5, 2000 – Dec. 26, 2001)

Table 6. Availability analysis of the klystron-modulator. (As of Dec. 26, 2001)

January 03 ,2001 ~ December 26, 2001 (real run 295 days)

Operation Period	'94	'95	'96	'97	'98	'99	'2000	'2001
Total No. of Mod.	11	11	11	11	12	12	12	12
Operation Time (hr)	4,752	7,152	6,432	7,128	6,816	5,616	6,936	7,080
Total Failure Counts	103	175	131	130	289	39	105	30
Total Down Time (hr)	563	1,076	413	529	468	116	340.1	171.3
System MTBF (hr)	28	41	49	55	24	144	74	230
MTTR (hr/failure)	5.46	6.15	3.15	4.07	1.62	2.97	3.24	5.71
Availability (%)	81	85	94	93	93	97.9	95	97.5

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 December of 2001 is shown in Fig. 2. In Table 8, the availability analysis of the system is listed since its installation. From Fig. 2, the fan and the CB trip of modulator have the highest fault count and the longest down time. And then, in order to reduce fault we replaced the modulator fan for long life-time and adjusted sensitive SCR gate hold and OCR.

The system availability in 2001 is approximately 97 %. From the Table 6, we can see the availability increases in 2001 compared to the previous years. At 2000, the system availability was about 95 %. The increase of availability has been caused by the decreasing klystron fault and thyratron fault rather than last year. The over-current was caused by thyratron misfire due to misleading timing signals and electronic circuit malfunction due to electrical noises. We are trying to reduce the system failure count further.

3 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 of high voltage run-time has accumulated over 60,000 hours operation time as of December 2001. 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. The system availability in 2001 is approximately 97 %. And then we will improve the control system of interlock which accumulated and logged the data and fault of the klystron-modulator system.

4 REFERENCES

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