RELIABILITY ANALYSIS OF THE PLS KLSYTRON-MODULATOR SYSTEM

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Abstract

Operational performance of the Pohang Light Source (PLS) linac klystron-modulator (K&M) system is analyzed. The system has been in operation since 1993. However, systematically accumulated data have only been available from 1997. Therefore, data collected from 1997 to 2000 are used for the analysis. Since the linac operation in 1993, three out of twelve klystrons has been failed. Based on the available failure data, klystron (Toshiba E3712) lifetime is anticipated as 110,600 hr. This lifetime is not yet realistic due to the lack of enough data. The anticipated lifetime will be constantly upgraded. An average accumulated run-time of the klyston is about 53,000-hr. Thyratrons (F-303) that are the most critical component in the PLS modulator has an anticipated lifetime of 36,500-hr. An average lifetime of failed thyratrons is 16,000-hr. Maximum accumulated run-time of the thyratron in PLS is about 40,000-hr. Overall availability of the K&M system is over 95 %.

1 INTRODUCTION

The PLS 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). Total 12 units of high power 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. We analyzed the reliability and availability of the K&M system from 1997 to 2000, especially klystrons and thyratrons that are the major parts of the system.

2 KLYSTRON AND MODULATOR

To satisfy PLS linac design requirements, Toshiba E3712 S-band klystron tube is selected as a main microwave source. Total twelve klystrons are currently under operation, and eleven out of twelve klystrons are E3712. At the linac pre-injector, a SLAC 5045 (60 MW peak) klystron is used. The modulator that mates with the klystron tube is manufactured in house.

2.1 Klystron

Operational frequency of both E3712 and SLAC 5045 klystrons is 2,856 MHz. Peak output powers of E3712 and SLAC5045 are 84 MW and 60 MW, respectively [1]. 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.

2.2 Modulator

Major specifications of the modulator are listed in Table 1 [1]. Normal operating repetition rate of the modulator is 30 Hz while the linac electron gun runs with 10 Hz rate. Two thyratron types are currently in use in the modulators: ITT F-303 and LITTON L-4888.

Table 1. 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

Forced air-cooling is used for the thyratrons. Two triaxial cables in parallel are used to make electrical connections between the PFN and a pulse transformer. The pulse transformer has 1:17 turns ratio. Components in a pulse transformer tank are immersed in high voltage insulating mineral oil. The klystron sits on the top cover of the pulse tank and is connected to a 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 [1, 2].

3 AVAILIBITY ANALYSIS

Status of the PLS klystrons is given in Table 2. The klystron in station 3 has the longest operation of more than 54,000 hours as of December 2000. Since the installation of the linac, three klystrons had been failed. Table 3 lists the failed klystrons. The klystron from the station 2 had electrode damages 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 2. Status of Klystron (As of Dec. 26, 2000)

MK No.	Klystron Model	HV Run(hr)	Heater Run(hr)	Installed Date
1	SLAC 5045 (S/N:511A)	49,460	55,593	93.07
2	E3712 (S/N:21011PLS)	53,979	39,207	95.08(18833)
3	E3712 (S/N:PLS002)	52,976	55,040	93.06
4	E3712 (S/N:74003PLS)	52,448	54,964	93.06
5	E3712 (S/N:89004PLS)	51,316	54,235	93.06
6	E3712 (S/N:14012PLS)	51,507	26,999	97.02(26772)
7	E3712 (S/N:66007PLS)	50,447	53,063	93.09
8	E3712 (S/N:82013PLS)	51,296	26,400	97.03(27290)
9	E3712 (S/N:41009PLS)	49,871	52,783	93.10
10	E3712 (S/N:98010PLS)	50,198	52,666	93.11
11	E3712 (S/N:77006PLS)	49,432	52,910	93.11
12	E3712 (S/N:93016PLS)	24,869	21,664	97.10

Table 3. Failure Status of Klystron.

MK No.(Model #)	HV Run(hr)	Heater Run(hr)	Installed Date	Problems
2(S/N:21011PLS)	50,051	35,238	95.08(18833)	Mag. Coil short, Arc(13 kV)
6(S/N:14012PLS)	47,600	23,041	97.02(26772)	Kly. Arc (14 kV), Mag. Noise
8(S/N:82013PLS)	47,476	22,436	97.03(27290)	Heater internal short

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. Statistical failure of the PLS klystrons has been analysed to predict the failure probability for a given period and to determine a suitable number of spares for providing a desirable operational availability. We assumed that life of a klystron follows a Weibull distribution with two parameters, where two parameters are statistically estimated as using the maximum likelihood estimation. We used the failure data that have been collected since 1993. Based on this analysis, mean life of a klystron is estimated as 110,675 hours. To determine an appropriate number of spares for klystron, we first estimate the probability that a given number of failures will occur in a specified period as in Table 4. We see in this table that no failures occur in one year with probability of 0.387, one or more failure will occur in one year with probability of 0.613 and so on. The suitable number of spares may depend on the allowable level of probability. One percent or five percent is the usual choice for the allowable level. If one percent is taken, for example, the suitable number of spares in one year would be four since the probability that four or more failures occur in one year is less than one percent. Even if we have four spares there will be a chance about 1 percent that four or more failures occur and the system may become unavailable, which we should tolerate that situation.

Table 4. Failure probabilities of Klystrons

#failures	In one year	In two years
none	0.3868	0.1354
1 or more	0.6132	0.8646
2 or more	0.2305	0.5695
3 or more	0.0573	0.2753
4 or more	0.0099	0.0979
5 or more	0.0012	0.0259
6 or more	0.0001	0.0051

Status of thyratron is listed in Table 5. The high voltage run-hour in Table 5 is the total accumulated hour, and it does not imply actual run-hour of the thyratron in the station. A thyratron that has the longest run-hour is the one in station 4. It reaches more than 55,000 hours. There are three main causes of thyratron failure: high switching jitter, out of reservoir ranging control, and internal electrode or grid short. Three models of thyratron have been used: CX-series, L-series, and F-series. The lifetime analysis is focused on F-series only. Failure analysis on thyratrons has been performed using failure data observed until November 30, 2000 and Weibull distributions. As shown in Table 6, the life of F-series is estimated three times longer than that of CX-series. A total of six CX-series were installed since 1993, which has been replaced by other models upon their failures. This table shows that the life of L-series is estimated as the longest, but it may not be reliable since it is based only four failures observed. Hence, we may conclude that installing F-series will be a desirable choice in a sense of system availability of modulators.

Table 5. Status of Thyratron (As of Dec. 26, 2000)

MK No.	Thyratron Model	HV Run(hr)	Heater Run(hr)	Replaced Date
1	ITT F -303(S/N:136)	49,460	21,817	97.11
2	LITTON L -4888(S/N:100032)	53,979	44,759(15261)	96.11
3	ITT F -303(S/N:828)	52,976	7,310	99.12
4	ITT F -303(S/N:107)	52,448	55,303	93.07
5	ITT F -303(S/N:832)	51,316	2,830	00.07
6	LITTON L -4888(S/N:100045)	51,507	44,950	94.12
7	ITT F -303(S/N:137)	50,447	21,681	97.11
8	ITT F -303(S/N:112)	50,296	53,952	93.11
9	ITT F -303(S/N:105)	49,871	53,622	93.12
10	ITT F -303(S/N:114R)	50,198	40,181	95.06
11	ITT F -303(S/N:831)	49,432	3,678	00.06
12	ITT F -303(S/N:138)	24,869	16,108	98.09

Table 6. Average lifetime of Thyratron

Models	**Average life (Hr)**	**Weibull parameters**	
		α	λ
F-series	36556.85	1.3	0.0000253
CX-series	11755.63	3.6	0.0000767
L-series	43407.45	1	0.000023

Table 7 shows the probability that an F-series thyratron in each modulator will have a failure in a specified period. In Table 7, the expected number of failures among thyratrons currently in use is calculated by summing the failure probabilities in a specified period. We expect that about one and two failures will occur in 6 months and 12 months, respectively.

Table 7. Failure probability of F-series Thyratron

modulator	Current operating hours	In 4320 hrs (6 months)	In 8640 hrs (12 months)
M01	15064.9	0.1046	0.2044
M03	2344.1	0.0707	0.1509
M05	0.0	0.0546	0.1291
M07	17438.1	0.1085	0.2109
M09	48833.8	0.1419	0.2665
M10	36478.6	0.1314	0.2489
M11	0.0	0.0546	0.1291
M12	10925.0	0.0967	0.1915
M04	51824.7	0.1442	0.2703
M08	50672.9	0.1433	0.2688
Expected # failures		1.0505	2.0704

We estimated the failure probabilities of thyratrons in a specified period and listed in Table 8. From Table 8, we may conclude that five spare thyratrons would be enough in one year to ensure 95 % availability if 5 percent is chosen for the allowable level since the probability that five or more failures will occur in one year is about 3 percent. In Table 9, availability of the overall K&M system is listed since its installation.

Table 8. Failure probability of Thyratrons

# failures	**In one year**	**In two years**
none	0.0646	0.0030
1 or more	0.9354	0.997
2 or more	0.7348	0.974
3 or more	0.39	0.8926
4 or more	0.1688	0.7417
5 or more	0.0322	0.514

Table 9. Availability of klystron-modulator system. (As of Dec. 26, 2000)

January 05, 2000 ~ December 26, 2000 (real run 289 days)

Operation Period	'94	'95	'96	'97	'98	'99	'2000
Total No. of Modulators	11	11	11	11	12	12	12
Operation Time (hr)	4,752	7,152	6,432	7,128	6,816	5,616	6,936
Total Failure Counts	103	175	81	130	289	39	106
Total Down Time (hr)	563	1,076	413	529	468	116	340.1
System MTBF (hr)	28	41	49	55	24	144	74
MTTR (hr/failure)	5.46	6.15	3.15	4.07	1.62	2.97	3.24
Availability (%)	81	85	94	93	93	97.9	95

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

In general, klystron vacuum has the highest fault count and the longest down time. K&M system in the station 7 showed bad vacuum behavior and was conditioned with high voltage for nearly a month in 2000. Thus, the system availability is reduced from 98% in 1999 to 95% in 2000. The system availability in 2000 was 95%. Current availabiltity of the K&M system is over 95% that is sufficient to serve as a full energy injector to the PLS storage ring. Injection takes place twice a day.

4 SUMMARY

The klystron and modulator systems are key devices in linac facilities. The PLS linac has 12 K&M systems. The klystron is Toshiba E3712 that operates in S-band and provides 80 MW peak output power. The PLS linac modulator has 200 MW peak power. The K&M system started its full operation in 1994. A K&M system with the longest operation time has accumulated nearly 54,000 hours as of December 2000. Availability analysis shows that the system is running very stable and reliable, and the performance has been continuously improved. The anticipated lifetimes of klystrons and thyratrons are about 110,600-hr and 36,500-hr, respectively. We conclude that four spare klystrons and five spare klystrons will ensure over 95% of K&M system availability.

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