KLYSTRON-MODULATOR SYSTEM PERFORMANCES FOR PLS 2-GeV LINAC*

M. H. Cho, J. S. Oh, S. S. Park, and W. Namkung
Pohang Accelerator Laboratory, POSTECH
Pohang 790-784, Korea

The PLS 2-GeV linac employs 11 units of high-power pulsed klystrons (80-MW) as the main RF sources. The matching modulators of 200-MW (400-kV, 500-A) can provide a flat-top pulse width of 4.4 µs with a maximum pulse repetition rate of 120-Hz at the full power level. For a good stability of electron beams, the pulse-to-pulse flat-top voltage variation of a modulator requires less than 0.5%. In order to achieve this goal, we stabilized high-voltage charging power supplies within 1% by a phase controlled SCR voltage regulator. In addition, we employed ac/dc feedback together with a resistive De-Q'ing system to achieve far less than 0.5% variation of the PFN charging voltage. This paper presents the main features of the klystron-modulator system and the characteristics of the pulsed high-power RF system performance during the beam injection operation for the Pohang Light Source commissioning.

I. INTRODUCTION

PLS linac has been injecting 2-GeV electron beams to the Pohang Light Source (PLS) storage ring as a part of the ring commissioning operation since September, 1994 [1]. The linac klystron-modulator (K&M) system has been in operation well before the ring commissioning, and the total accumulated high voltage run time of the oldest unit has reached beyond 14,000 hours [2]. The K&M systems are normally operating in 70 to 80% of the rated peak-power level to avoid the multipactoring phenomena occasionally occurred in a random fashion for the waveguide networks and accelerating structures of the linac system. Considering total 11 K&M systems installed in the PLS linac, the sum of all the high voltage run time is approximately 120,000 hours.

In this paper, we review overall system performance of the high-power K&M system. A special attention is paid on the analysis of all failures and troubles of the K&M system which affected the linac RF operations as well as beam injection operations for the period of September 1994 to March 1995. During this period, the machine has been in the operational mode for total 198 days. Summer shut-down (1.5 month) and the scheduled maintenance shut-down time are excluded in the analysis.

II. K&M SYSTEM OVERVIEW AND PERFORMANCE

The key features of the K&M system design include the 3-phase SCR controlled AC-line power control, resonant charging of the PFN, resistive De-Q'ing, end-of-line clipper with thyrite disks, pulse transformer with 1:17 step-up turn ratio, and high power thyratron tube switching. The major operational parameters of the PLS-200-MW klystron-modulator system are listed in Table 1. The details of the system design and performance characteristics are described elsewhere [2].

Table 1. Operation parameter summary for klystron-modulator.

Peak beam power	*200-MW max.* (400 kV @500A)
Beam vol. pulse width	ESW 7.5µs, 4.4µs flat-top
Pulse rep. rate	120 pps *max.* (currently 30 pps)
PFN impedance	2.64Ω (5% positive mismatch)
Voltage stabilization	SCR, DC feedback & 5% De-Q'ing
Pulse transformer	1:17(turn ratio), L_{lk}:1.3µH,C_{st}:69nF
Thyratron switch	Heating factor: 46.8×10^9, 8.5 kA peak anode current
Klystron tube	Drive power:~300 W, efficiency:40%, gain:~53dB, peak power:80/65 MW (currently running at 50 to 65MW)

The shot-to-shot beam voltage stability is controlled by (1)the feedback of the DC high voltage from PFN to SCR primary input voltage control and (2)the resistive De-Q'ing. SCR DC feedback provides less than ±0.5% fluctuation, and additional De-Q'ing stabilizes the beam voltage better than ±0.1% fluctuation level. Fig. 1 shows the sample traces of the beam voltage accumulated more than an hour which exhibits less than ±0.1% fluctuation.

For the fault free stable operation of the system, the thyratron tube is one of the most important active components which require continuous maintenances and adjustments. The thyratron tubes which meet the PLS-200-MW system specifications are listed in Table 2 together with their specifications. ITT/F-303 and Litton/L-4888 are installed in our system, and the performance evaluations are underway. EEV/CX-1836A will be installed also for the comparison. This effort is initiated to improve the system from the frequent occurring faults (see Fig. 2) caused by the irregular recovery action of the thyratrons, which strongly depends upon the reservoir control.

There are three types of system interlocks, namely dynamic, static, and personal protection interlocks. All the static fault activation is initiated by the relay logic circuit, and the dynamic faults which require a fast action response are activated using the electronic comparator circuit. When the system operation is interrupted by the static fault, it can be recovered either by the

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remote control computer or manual reset. However, we have been performing all manual resets for the purpose of the experience accumulation, such as to find the type of troubles and system bugs which can provide the idea of the system improvement. The statistical analysis of the machine availability presented in this paper is based on the operation method of the manual reset by the maintenance crew only, without using the remote computer control. On the other hand, in the case of dynamic faults, the system recovers automatically without the help of the control computer when the condition returns to a normal state.

Table 2. Comparison of the thyratron tubes.

ITEM	ITT F-303	Litton L-4888	EEV CX-1836A
Heater (Vac/A) *max*	6.6 / 80	6.7 / 90	6.6 / 90
Reservoir (Vdc/A) *max*	6.0 / 20	5.5 / 40	6.6 / 7
Peak anode (kV/kA) *for*	50 / 15	50 / 10	50 / 10
Peak anode vol.(kV) *inv*	50	*n/c*	50
Avg. anode cur.(A) *max*	8	8	10
min DC anode vol.(kV)	2	10	5
Heating factor ($x10^9$) *max*	300	400	*n/c*
dI/dt (kA/μs) *max*	50	16	10
Anode delay (μs) *max*	0.3	0.4	0.35
Trigger jitter (ns) *max*	2	10	10

III. SYSTEM AVAILABILITY STATISTICS

Since the completion of the PLS 2-GeV linac installation in December 1993, all the K&M systems have been operating continuously except scheduled short terms and a long term summer shut down. Table 3 shows the total accumulated times of klystron's and thyratron's heater operation, and the high voltage run. Sum of the high voltage run time of each modulator has reached over 120,000 hours, and the experience accumulated so far provides the valuable information for the system's stable operation. Fig. 2 is the Pareto chart of the total system's static fault count data collected for the period of September 1994 to March 1995. Net operation days during this period is 198. As mentioned in the previous section, the reset has been done by the maintenance crew only, and the most of nights and weekends during the 198-days, no extra maintenance work has been performed. Therefore the down time for the circuit breaker (①CB) trip which occurred the most frequently is unusually high among others. Other faults, such as fan(③) and key switch(⑥) are due mainly to faulty components, which no longer occur in any appreciable numbers after the replacement.

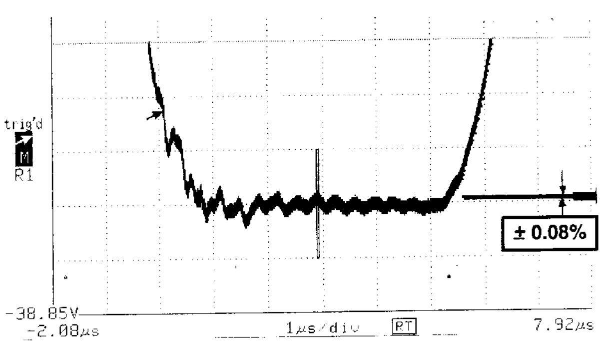

Fig. 1. The flat-top ripple and the cumulative (>1 hr) stability measurement of the klystron beam voltage (Tektronix DSA-602 signal analyzer is used) with DCHV feedback & De-Q'ing.

Table 3. Accumulated run times (in hours) of the PLS 2-GeV Linac's K&M systems (total 11 sets); on April 21, 1995.

Unit No.	H.V. run time	Kly. heater	Thyratron
MK-01	11,498	13,435	13,639
MK-02	14,025	13,111	13,252
MK-03	12,710	13,376	15,464
MK-04	11,784	13,326	13,541
MK-05	11,137	12,719	13,215
MK-06	11,135	12,284	3,135 (*1)
MK-07	10,040	11,456	12,246
MK-08	10,966	12,276	12,189
MK-09	9,879	11,320	11,730
MK-10	9,784	11,138	7,758 (*2)
MK-11	9,848	11,251	4,908 (*1)

*1) Thyratrons replaced with L-4888 due to the failure of F-303.
*2) Thyratrons replaced with F-241 due to infant failure of F-303.

Machine availability analysis has been performed based on the data using the techniques described in detail in reference [4]. The results are summarized and compared with the SLAC's in Table 4. The MTBF stands for the mean time between failures, and it is calculated by dividing the sum of the accumulated modulator run time with the total fault count ($MTBF = N*TO/FC$). The MTTR (mean time to repair, which is equal to the total down time divided by total fault counts, $MTTR = TD/FC$) is rather longer than the SLAC's. This excellent performance is due to the extensive inspection work of the entire system for the trouble shooting as well as crew training for the system maintenance. Especially, the lack of the experience on the thyratron operations and severe EMI environment have contributed a lot for the longer MTTR.

Only 71% of the machine availability ($A = 1-MTTR*FC/TO$) has been obtained with the regular type maintenance of 44-hr-work-per-week. However, during the beam operation mode when the maintenance crews are standby, approximately 91% of availability has been reached. It indicates most of the system troubles are not so serious, and in many cases they are easily recoverable.

Table 4. Comparison of the K&M system fault analysis based on the data for the period of September 1994 ~ March 1995.

ITEM	*PLS*[*2]	*SLAC*[4]
Number of modulators, ***N***	11	243
Spare no. of modulators	0	14
Operation time (hr)[*1], ***TO***	4752	4000
Total failure counts, ***FC***	168	997
Total down time (hr), ***TD***	493 (1150)	401
MTBF (hr)	311	975
MTTR (hr/failure count)	2.6 (6.8)	0.4
System Availability, ***A***	0.91 (0.71)	0.94[*3]

*1) Operation time for the statistical analysis.
*2) Numbers in ( ) indicates the standby RF operation mode without extended hour maintenance work (only 44 hr/week).
*3) Standby spare unit included

IV. COMMENTS ON SYSTEM TROUBLES

The most frequent system fault is the circuit breaker (CB) trip as shown in Pareto chart. This is due mainly to the problems in thryratron recovery actions which require elaborate reservoir rangings. Thyratron tubes of F-303 and L-4888 require ranging adjustment (see Table 2). According to our experience, they are changing in irregular patterns such that there exist no normal patterns or pre-symptoms which can be used for the preventive maintenance. Once it is out of normal operating point, there occur self-fire, firing miss, or slow recovery. The CX-1836A thyratron tubes require not so delicate ranging according to the manufacturer's specifications, and we are planning to test them in the near future.

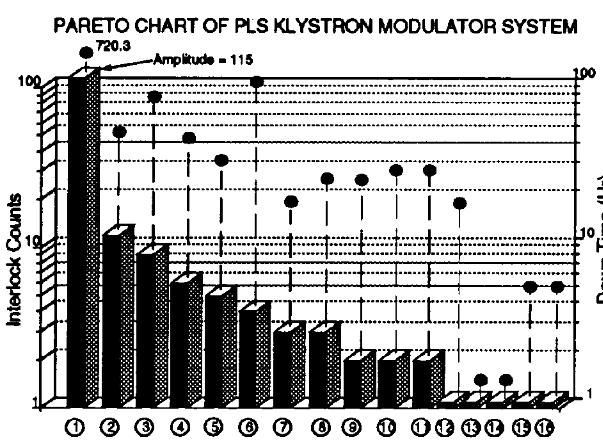

Fig . 2. Pareto chart of the system fault statistics. Numbers in the x-axis indicate type of faults; 1) CB trip, 2) klystron vacuum, 3) cooling Fan, 4) thyratron grid circuit, 5) core bias current low, 6) key switch, 7) DCPS overvoltage, 8) magnet current low, 9) core bias current high, 10) SCR gate hold, 11) ground hook, 12) magnet temperature high, 13) thyratron heater, 14) PFN RC-snubber, 15) SCR control board replace, 16) De-Q current high. Solid circle indicates down times, and the bar indicates interlock counts.

Klystron tubes also showed an internal arcing causing the vacuum pressure trip in a random fashion (see ② in Fig. 2). When this occurs in a row, we could recover to the normal operation after performing the short pulse processing (with approximately 1 μs pulse width) for more than one day.

Other frequently occurred troubles are caused by the corona discharges. They occur when bad contacts exist in high voltage components, especially for the components which are connected by the spring action sockets. It has been found also that even a small corona discharge disturbs the ground potential, which are configured to have a single point ground connection inside the modulator, causing noise interferences in digital displays as well as SCR phase controls. Occasionally, this kind of EMI also affects LCD type displays of the nearby electronic equipment without affecting the performance, which became one of the normal check points for the systems.

V. SUMMARY

It is approximately 10 months since the PLS 2-GeV Linac has started its normal operation. We have analyzed the klystron modulator system's performance record for the period of the recent six months. It is observed that the reliability of klystrons is well over our expectations compared with other components in the modulators. The life time of thyratron tubes appears to be reasonable except the occurrence of infant failures. However, the major improvement is necessary for the reservoir control which is the main source of system troubles. The machine availability statistics of the K&M system for the beam operation mode (typically 2 operators are on-duty) is calculated to be over 90%. It appears to us that there are still lots of rooms for the improvement toward the availability more than 95% with proper choices of the protection circuits and control logic.

VI. REFERENCES

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