KLYSTRON-MODULATOR SYSTEM PERFORMANCE FOR THE ADVANCED PHOTON SOURCE LINEAR ACCELERATOR*

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Abstract

The S-band linear accelerator (linac), which was built to be the electron source and the front end of the Advanced Photon Source (APS) injector, is now also being used to support a low-energy undulator test line (LEUTL) to drive a free-electron laser (FEL). The APS linac system employs five units of pulsed high-power klystrons (35-MW class) as the main rf sources. The matching pulse modulators provide high-voltage pulses running at 280 kV and 300 A with 3.5-μs pulse width and a nominal pulse repetition rate of 30 Hz. The system availability of the entire APS linac during the last run period of calendar year 2000 was estimated to be slightly over 95%. We present a discussion of the reliability and various fault statistics of the klystron-modulator system together with the key features of the system hardware.

1 INTRODUCTION

The Advanced Photon Source (APS) linear accelerator system [1,2] consists of five S-band high-power klystron and modulator systems, thirteen accelerating structures, and three SLAC-type energy doubler cavity sleds all running at 2,856-MHz frequency. The system has three electron guns; two thermionic rf guns, mainly used to support APS injections; and one photo cathode rf gun to support the FEL project. Normal experimental projects during user beam are the LEUTL-FEL studies [3], which require highly reliable linac performance with machine availability as high as possible. Since the completion of the APS linac in 1994, there have been a number of upgrade efforts to improve the system reliability and availability, such as installation of a precision temperature control system, a low-level rf system, a pulse modulator system [4,5], the bunch compressor, and a high-power waveguide switch network installation [6].

In this paper, we review overall system performance of high-power klystron and modulator (K&M) systems. These systems are known to be the major source of trouble in the linac. Special attention is paid to the analysis of all failures and trouble associated with the K&M system for the run period in 2000. During this period, the scheduled user beam time of the APS was approximately 5,040 h, and the linac performance evaluation was carried out based on this operation schedule, even though there has been no beam injection interruption to the APS storage ring by the linac rf system fault.

2 LOW-LEVEL RF SYSTEM

The low-level rf (LLRF) system is principally housed in two separate cabinets for each K&M system: a VXI-based measuring system and a klystron drive system. The klystron drive system uses a pulsed solid-state amplifier together with NIM modules and an rfi-tight chassis, i.e., each klystron has its own drive amplifier, allowing operational flexibility for fine-tuning of the machine. VXI-based rf phase and amplitude data collection provides precise tuning and operational repeatability. Detailed technical information regarding the system is provided in Ref. [7].

3 KLYSTRON & MODULATOR SYSTEM

The original design of the K&M system for the APS linac employed a conventional DC high-voltage power supply based on a full-wave bridge diode assembly and a resonant charging circuit [4]. One of the unavoidable disadvantages of this system is the circuit breaker trips caused by arcing at the load side during the 'On' state (before the recovery) of the thyratron. This problem is attributable to the DC high-voltage power supply, which sees the arcing as a short circuit. With extensive field-tests, the modulator's high-voltage charging system has been redesigned to use a constant-current, high-frequency inverter power supply (EMI-303), which has 30 kJ/sec charging capability. The detailed performance test results are well documented in Ref. [5]. The redesigned circuit schematic of the APS modulator is shown in Fig. 1.

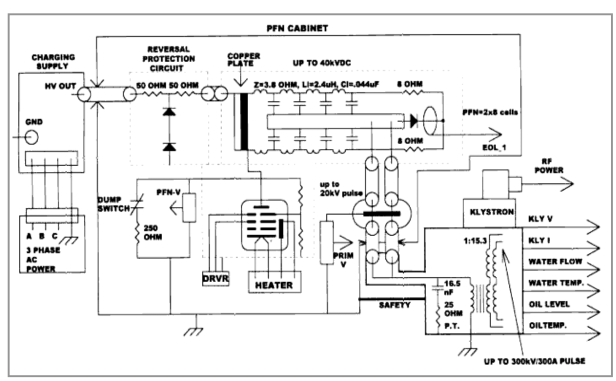

Figure 1: Circuit schematic of APS klystron modulator.

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Pulse-to-pulse klystron beam voltage stability is typically observed to be within 0.3%, with more than 5% AC-line voltage fluctuations. The EMI-303 system shows good noise immunity to klystron arcing even at the full cathode voltage of ~300 kV. With the proper dwell time control, one can avoid extended high-voltage holding time at the thyraton anode. Fig. 2 shows a typical PFN charging voltage waveform by EMI-303 high-voltage power supply.

An EEV-1836A thyratron tube is employed for the high-power switching in the modulator. Table 1 shows specifications of the TH2128 klystron tube used in the APS linac rf power source.

Table 1: Specifications of TH2128 Klystron Tube

Frequency	2856 MHz
Peak output power	35 MW
rf pulse length	6 µs
Peak beam voltage / current	300 kV / 300 A
Perveance (*10-6)	1.9 ~ 2.15
Max. drive power	400 W
Tube gain (typical)	52 dB
Tube efficiency	42%

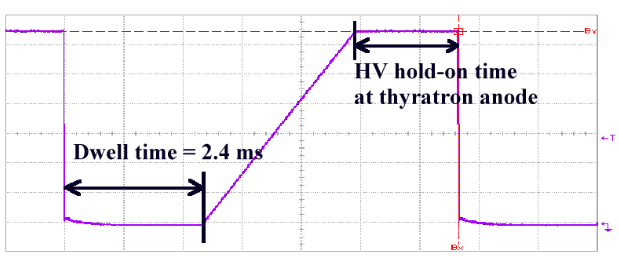

Figure 2. Typical PFN charging voltage waveform. Arrow indicates the dwell time of 2.4 ms (vertical scale: 5 kV/div, horizontal scale: 5 ms/div).

4 OPERATIONAL STATISTICS

Every year, APS is scheduled to deliver approximately 5,000 h of beam operation to users. The APS linac system is supposed to be ready to inject the beam whenever necessary, either because of a fault or a three times daily scheduled fill. For the reasonable preparation of spare parts, the lifetime statistics of the semi-consumable components (such as klystron and thyratron tubes) are very important. Table 2 shows klystron and thyratron heater run times as of February 5, 2001.

The numbers indicate current status since run timers are set to zero when new tubes are installed. So far six klystron tubes have been replaced. The average lifetime of a klystron tube is 24,216 h and that of a thyratron is 14,991 h (below 1,000-h infant failure is excluded in the statistics).

Table 2: Klystron and Thyratron Run Times

Unit No.	Klystron heater time	Klystron HV time	Thyratron heater time	Remarks
L1	30,258	29,857	6,619	PC gun
L2	29,682	29,406	13,057	RF gun
L3	1,064	1,012	20,375	
L4	30,130	27,705	6,889	
L5	4,294	4,086	13,392	
Average	19,086	-	12,066	

The K&M system is operated by the Experimental Physics and Industrial Control System (EPICS)-based remote control. The local control and monitoring of the K&M system is based on Programmable Logic Control (PLC), and the control data networking is done through the digital I/O communication to VME. The major functions of the local PLC are system interlock control, parameter monitoring, and control. Interlock activation caused by klystron and/or modulator operation leads to the disabling of the high-voltage charging power supply (EMI-303) followed by the activation of the high-voltage dump switch. In the case of waveguide pressure rise beyond the critical set-point or exceeding the VSWR set value (by an arcing in the waveguide and/or accelerating structures) will activate a fault situation by turning off the solid-state drive amplifier.

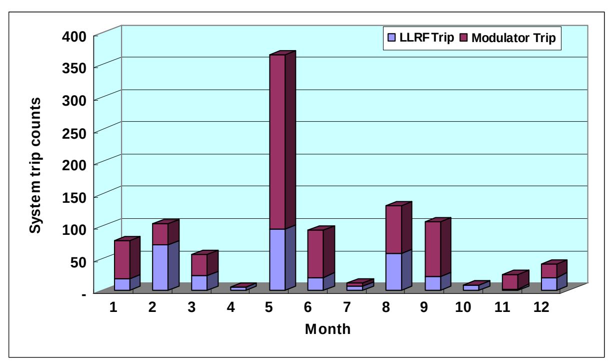

Figure 3: Monthly fault count statistics of the APS klystron modulator system (from L1 to L5).

For system performance evaluation, as well as operator training, all types of K&M and LLRF faults are handled manually. The monthly fault count statistics for LLRF and K&M during 2000 operation are shown in Fig. 3.

Very low counts in April, July, and October are due to the rather long maintenance shutdown. The typical cause of an LLRF fault is either VSWR or a waveguide vacuum caused by the rf processing operation right after the maintenance period. The most frequent modulator fault is attributable to the noise interference caused by the thyratron firing. The cause of the high fault count in May turned out to be irregular sparking at the interior of the thyratron tube. The sparking was hard to identify until a black burn mark penetrated outward. Through extensive noise tracking, achieved by measuring the differential current of the various signal cables using the rf current probe (Fisher Custom Communications Model F-35-1), we managed to lower the noise amplitude more than 10 dB (on average) by adding high-frequency ferrite cores to noise carrying cables.

Based on the fault count statistics with the linac down-time information, the machine availability analysis has been performed using the method described in detail in references [8,9]. The results are summarized and compared with the SLAC (Stanford Linear Accelerator Center) and the PLS (Pohang Light Source) statistics in Table 3. The mean time between failures (MTBF) is calculated by dividing the sum of the accumulated modulator run time by the total fault counts (*MTBF = N*TO/TC*). The mean time to repair (MTTR) is equal to the total down time divided by total fault counts (*MTTR = TD/FC*). The availability, *A*, is calculated by the equation,

$$A = 1 - MTTR*FC/TO$$

Table 3: Comparison of the APS Linac K&M Fault Statistics with Those of SLAC [8] and PLS [9]

Item	Unit	PLS (1995)	SLAC (1991)	APS (2000)
No. of modulators (N)	#	11	243	5
Linac scheduled run time (TO)	h	4,752	4,000	6,400
Total modulator run time (N*TO)	h	52,272	972,000	32,000
Total fault count (FC)	#	168	997	1,026
Total unscheduled down time (TD)	h	493	401	342
Overall modulator failure rate (FC/TO)	#/h	0.035	0.249	0.160
MTTR (TD/FC)	h	2.9	0.4	0.3
MTBF (N*TO/FC)	h	311.1	974.9	31.2
Availability (A)	%	89.6	90.0	94.7

The information about the linac down time was rather limited, except long repair times for the tube replacement job or modulator circuit repairs. For this reason, the TD in the table was estimated to be approximately 15 min per fault. Typical fault reset time was less than 5 min on average when there was no apparent system damage. As the table shows, APS linac shows excellent availability, reaching close to 95% even with the handling of all kind of faults by manual reset work on EPICS-based remote control. Note that SLAC and PLS systems employ auto reset by OP-amp-based comparator circuits and the system control software [8,9].

5 SUMMARY

This paper provided an overview of the overall performance of the klystron and modulator system of the APS linac in 2000. Typical sources of faults in the K&M system were observed to be (1) the well-known noise interferences from the thyratron switching action and, (2) unexpected troubles in irregular patterns such as random high-voltage sparking at high-voltage terminals and components. Especially because of the high demand in normal beam operation, sometimes a small problem evolves into serious repair work. For this reason, it is necessary to build intelligent diagnostic trees to predict or identify potential problem spots based on the data collected through a K&M control system. Employing constant-current inverter power supplies proved to be an excellent choice for better stability as well as improved reliability. The current availability, 94.7% is satisfactory; however, efforts aimed at further improvement are underway, such as employing auto reset control for the non-critical faults, high-power waveguide switch network installation, etc. to achieve far better performance.

6 ACKNOWLEDGMENT

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