# OPERATIONAL EXPERIENCE WITH SLAC ENERGY UPGRADE*

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## Summary

To produce energies of over 50 GeV for SLC, all klystron stations on the accelerator are being upgraded to produce 250 MeV energy contribution per station. This involves installing new, higher power, longer pulse klystrons, upgrading klystron modulators to provide these higher voltage, longer klystron beam pulses, and a new interlock and protection system.[1] A new VAX based diagnostic system including automated microwave measurements, klystron beam monitors, and modulator performance checks is being implemented. Figure 1 shows a block diagram of the klystron-modulator system. To date, over half of the new klystrons have been installed and tested, the modulator upgrade program has converted 22 sectors (8 stations each) of modulators out of 30, and a four sector sampling of klystrons has been run at full SLC specs, namely 350 kV beam voltage, 3.5 microsecond pulse duration, peak output power in excess of 60 MW, and PRF of 120 pps. This paper discusses the klystron design, modulator design, interlock and diagnostic systems, and the results of the initial operation.

## 5045 Klystron Design

The new klystron type being installed in the LINAC for SLC operation was originally designed to deliver a 5 microsecond RF pulse at a peak power of 50 MW, and an average power of 45 KW, hence the designation, 5045.[2] During the original developmental testing, it was found that this klystron would also operate at higher voltage, 350 KV, and shorter pulse width, 3.5 microseconds producing a peak output power of from 60 to 70 MW with even slightly higher efficiency. This higher level, but shorter duration peak power level, when stored in the

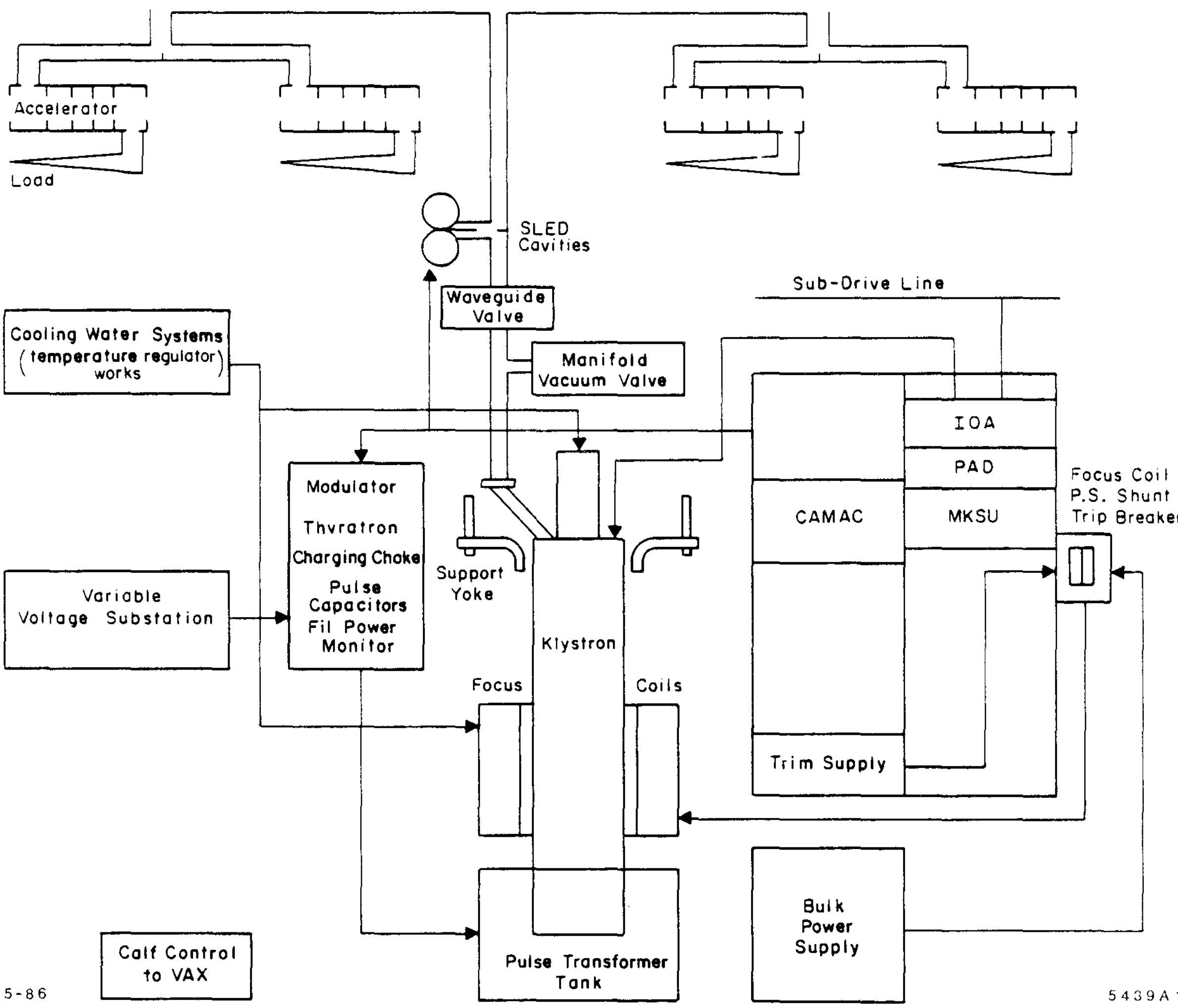


Fig. 1. Klystron Modular Systems.

*Work supported by the Department of Energy, contract DE-AC03-76SF00515.

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energy doubling SLED system yielded further efficiency gain due to decreased SLED cavity losses. The shorter pulse also produces fewer RF breakdowns in the klystron output gap and windows in spite of the higher peak fields involved. The table below gives the 5045 klystron operating parameters:

| | |
|---|---|
| Operating Frequency: | 2856 MHz |
| Number of cavities: | 6 |
| Beam Voltage: | 350 KV |
| Beam Current: | 414 Amps |
| Microperveance: | 2.0 |
| Output Power (peak): | 67 MW |
| RF Pulse Width: | 3.5 usec |
| PRF: | 180 pps |
| Efficiency: | 46% |
| Gain: | 53 dB |
| Cathode Current Density: | 8 A/cm2 |
| Cathode type: | dispenser |

Early development single window tubes experienced window failures at high power levels, so the current tube production uses waveguide splitters and combiners to put half of the tube power through each of two windows. These windows were at first mounted horizontally because of symmetry and ease of manufacture, but when foreign particles from both installation and existing waveguide connections accumulated on windows causing arcing and puncture, the window design was revised for vertical window placement. The current production klystron is shown in Fig. 2.

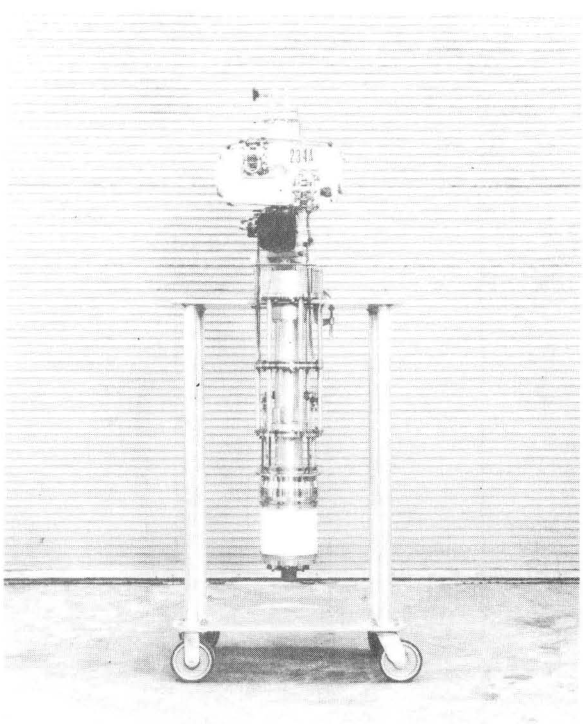

Fig. 2. 5045 Klystron.

Two other areas of design difficulty occurred during early manufacturing, cathode gassing problems, and RF output instability. In the manufacturing process of dispenser cathodes, organics are used which must be subsequently removed. If this removal process is not complete, a gassy cathode in the klystron results which limits tube life, or causes the tube to fail altogether. An increased level of quality control has minimized this problem in current production tubes. RF instabilities characterized by RF envelope modulation in the 10 to 30 MHz region varying with drive level plagued early production tubes. The phenomena is not completely understood to date, but readjusting intermediate cavity frequencies, and more careful control of cathode-anode beam dynamics has minimized the effect. The effect seems to be a function of beam perveance, and in cases where a particular tube is unstable at space charge limited heater power, reducing the heater power to a slightly temperature limited condition usually brings the tube into stable operation without loss of efficiency or output power. Further research is being done in this area.

Klystron lifetime in the absence of early catastrophic failures is based on dispenser cathode lifetime. These tubes have scandate enhanced cathode emitters which operate at a fairly low brightness temperature of 1,000 C giving a peak emission of 8 A/cm2. At such a temperature, the loss of barium from the cathode is very low, and a long cathode lifetime of 30,000 hours can be expected. The performance of 5045 klystrons installed in the accelerator supports this lifetime projection. Actual performance of installed klystrons is described in the last section of this paper.

### Modulator and Pulse Tank Redesign

The existing SLAC klystron modulators have been operating with little change for twenty years. The new 5045 klystron requires increased beam voltage, increased beam current, and a longer beam pulse. Modulator upgrading to the new specifications was planned making use of as much of the existing modulator circuitry as possible to minimize costs. Twenty years of operation in a dusty and environmentally uncontrolled location had taken its toll on modulator components. The modulator upgrade program starts with removing all components and wiring in the high voltage sections, and steam cleaning the empty cabinet. Parts to be reused are cleaned and retested, and many new components such as charging chokes, DC and pulse capacitors, pulse lines, and thyratron support electronics are installed. The rebuilt modulator is carefully inspected, and run to full SLC specs on a water load.

To mate with the much larger 5045 klystron, a new oil filled pulse tank was designed. Initially, a 14:1 ratio pulse transformer was used to provide 320 KV beam voltage pulses, but when the decision was made to run at 350 KV, the turns ratio was increased to 15:1. The new modulator, pulse tank combination has run quite successfully for many thousands of hours verifying the basic design. The more stringent specifications of the new system pushed the state of the art in several areas of component design, notably, pulse transformers, thyratrons, and pulse capacitors. The higher klystron cathode voltage in the pulse tank coupled with the need for internal water cooling gave rise to oil-water contamination faults, and some high voltage breakdown of tank pulse bypass capacitors. A significant number of pulse tanks experienced early failure during gallery operation. The causes are now understood, and modifications are in progress.

Thyratrons were the subject of much initial concern and experiment. To decrease peak current loading on individual thyratrons, some modulators were outfitted with dual sockets for use with two thyratrons operating in parallel. Both single and dual thyratron installations have operated satisfactorily at SLC specs, and thyratrons from a variety of manufacturers are successfully being used.

There were initially two sources for pulse capacitors, but the first delivery from one source failed in test. The second source provided capacitors that were installed in 100 modulators that ran successfully for over 5,000 hours. Then, a significant number of pulse capacitors began swelling and arcing. Autopsy revealed a progressive corona problem that would eventually lead to the breakdown of all capacitors. Both manufacturers now have new designs that show promise of running at SLC specs without breakdown, and the replacement process is beginning.

## Interlock and Diagnostic Systems

Significant operating parameters of each klystron-modulator system are monitored and controlled by the SLC VAX computer. Some hardware interlocks have been retained, but most interlocks are now in software via the Modulator Klystron Support Unit (MKSU).[3,4] It is significant that no klystrons have been damaged as the result of hardware or software interlock failure. The MKSU contains several diagnostic features that allow both the klystron beam voltage and current pulses to be remotely plotted in the control room, or on any graphics terminal. Jitter mode analysis for these and other parameters is available. A new control and monitor interface unit is presently being installed in modulators that will permit the SLC VAX via the MKSU to monitor klystron filament power and modulator performance, and also turn modulators on and off, or reset interlocks.

The microwave performance of individual klystrons is of paramount importance to the operation of SLC. Output power and phase must remain stable both during the pulse, and from pulse to pulse. A microwave measurement system called a Phase and Amplitude Detector (PAD) is installed in each klystron station.[5] The PAD block diagram is shown in Fig. 3 and consists of a precision automatic phase bridge and microwave linear detector that can sample either phase or amplitude anywhere in the RF pulse, record complete phase and amplitude plots taking successive time samples, or record phase and amplitude jitter or long term drift. Resolution of the amplitude detector is 0.1%, and phase resolution is 0.1 degree.

An illustration of a typical amplitude and phase plot including the energy doubler feature (SLED) is shown in Fig. 4. Pulse-to-pulse jitter is in the order of ± 0.2% for amplitude and ± 0.2 degrees for phase. Long-term stability is influenced by high voltage stability, cooling water temperature, and ambient temperature. A 1% change in high voltage causes a 1.5% change in output amplitude and a 6 degree change in phase. A cooling water temperature change by 1 degree F produces an amplitude change of 0.6% and a phase change of 1 degree. Variations in klystron heater power have an effect of 3 degrees phase per 1% power change for cathodes operating in the temperature limited range for RF stability. High voltage, cooling water temperature, and klystron heater power are all regulated. To correct remaining phase errors, a feedback loop through the VAX computer periodically resets the output phase of each klystron via a PAD measurement to a reference value. A plot of the output amplitude and phase of a typical klystron over a twenty-four hour period is shown in Fig. 5.

## Klystron System Performance

Operation at SLC specs called for much higher peak and average powers in both modulator components, and RF systems. RF loads, accelerator guides, waveguide feeds and power splitters, SLED cavities, and waveguide valves all have the potential of RF breakdown at the increased operating levels. Early in the checkout program, we experienced arcing in the waveguide valves, and it became obvious that the existing Indium sealed valves would not carry the increased power. A sector of valves were removed and replaced with thru waveguide sections

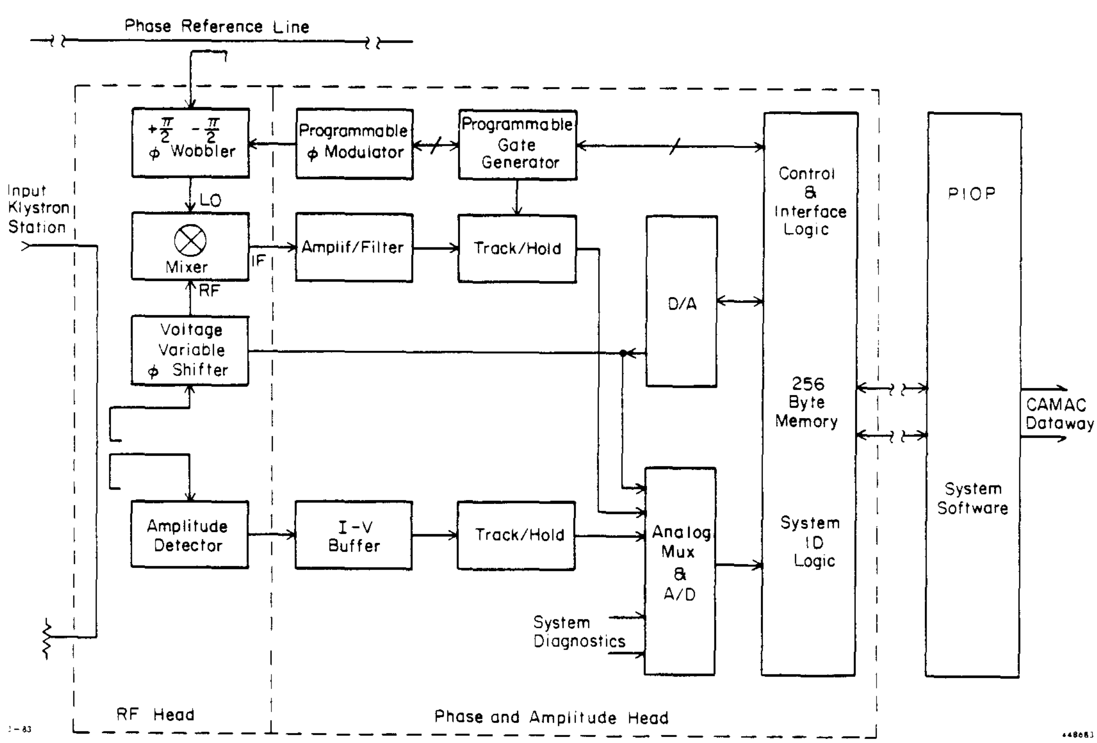


Fig. 3. Phase/amplitude detector block diagram.

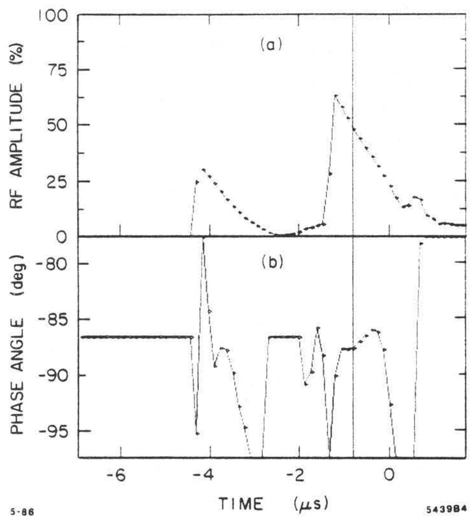


**Fig. 4. Amplitude and phase of typical RF pulse including SLED.**

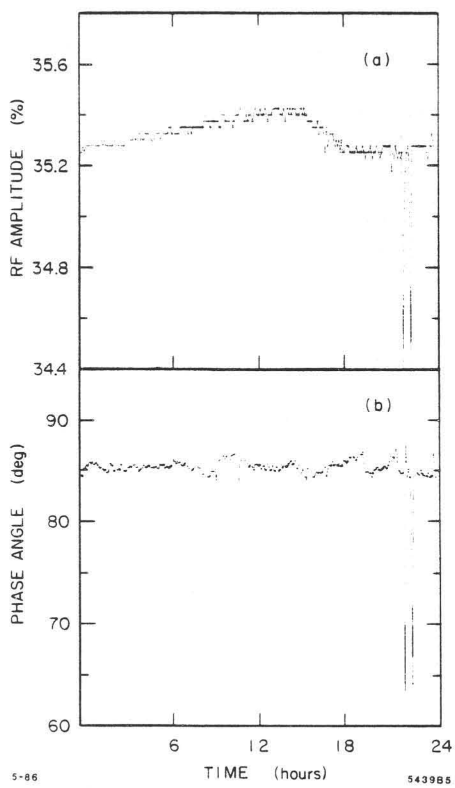


Fig. 5. Amplitude variations in % (a) and phase variations in degrees (b) over 24 hour period. (At hour 22:00 the klystron drive was removed twice.)

(spool pieces). With the valves removed we were relieved to find every other RF component handled the increased power demand. The valve was redesigned to accommodate higher power operation, and a rebuilding program is now in progress.

From January of 1985 through March of 1986, 38 new klystrons were operated at full SLC power specs, and the energy contribution of each SLEDed station was measured. The needed 250 MeV beam energy contribution from each station was achieved. This operation showed a number of design and fabrication weaknesses, but no major design faults surfaced. After processing, the RF system operated without faulting, and the klystron and modulator random faulting rate was within specifications. There were the predictable early failures, but no long term degradation effects were observed that would indicate short klystron life. The analysis of those failures that did occur is summarized in the last section of this paper.

## Failure Analysis and Lifetime Projections

After the Winter run concluded in March, a number of the new klystron units were returned to the Test Laboratory for various malfunctions and evaluation. Twenty of these returned klystrons had been run at SLC operating conditions for enough hours to generate preliminary reliability data. Of the twenty klystrons units returned, fourteen either had defects unrelated to the klystron tubes, or were found to be acceptable on retest. Six klystrons had failed, or were below SLC specs. Of these, four were early production units that had marginal performance at installation, but were run to obtain extended life data. Three of the tubes had gassy, or low emission cathodes, and it was of interest to see if these problems would clear up with time. They did not. The fourth tube had marginal stability in initial test, but was tried in a gallery socket to see if stability would improve. This did not prove to be the case.

The two failed klystrons had broken windows. There was evidence of debris on both klystron windows which caused arcing, and cracking or window puncture. Both windows on one tube failed before full power testing. The second window failure, a puncture, did not show up during operation, the tube ran 500 hours at full SLC specs, but leaked during sector venting.

The 38 klystrons that were the subject of the lifetime and failure analysis ran for a total of 11,386 hours at full SLC specs with only one klystron failure during running. The total running time of the tubes, most of it at 35 MW, 60 PPS was 91,676 hours. Assuming the principal cause of window failure is debris on the window, more careful assembly procedures coupled with the change to vertical window klystrons should minimize this failure mode. Our experience so far indicates that the normal ageing process in 5045 klystrons will be associated with cathode deterioration, and based on the presently available data, the average lifetime is estimated to be 20 to 30 thousand hours. The testing program also indicates that klystrons with gassy or low emission cathodes in initial test do not improve with age, and klystrons which are only marginally stable in the Test Lab will prove inadequate when operated in the Gallery environment. Design changes have been implemented in the production process to minimize these conditions, and no tube will be put on line that exhibits these deficiencies. Production efficiency from tube starts to delivered SLC spec tubes is up to nearly 80%, a very high percentage for the industry.

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