

THE SLC ENERGY UPGRADE PROGRAM AT SLAC*

G. A. LOEW, M. A. ALLEN, R. L. CASSEL, N. R. DEAN, G. T. KONRAD,
R. F. KOONTZ AND J. V. LEDACQZ
Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305

Introduction*

The SLAC Linear Collider (SLC) must reach a nominal center-of-mass energy of 100 GeV to fulfill its high energy physics goals.¹ This paper describes the energy upgrade program that is being implemented on the SLAC linear accelerator to meet these goals. It includes a discussion of the design requirements and available technical options, the rationale for the adopted solution, and the technical problems involved in the engineering and production of klystrons and modulators.

Requirements and Available Options

The SLAC linear accelerator is made up of thirty sectors, each containing nominally eight 40-ft girders. Each girder has four 10-ft accelerator sections which, when connected to a klystron of peak power P_{MW} and a pair of SLED cavities,² produces a no-load electron energy

$$V_{MeV} = 20 S \sqrt{P_{MW}} \quad (1)$$

where S , the SLED gain, is a function of various cavity, accelerator and pulse length parameters. Since the cavity and accelerator parameters are fixed by construction, the only variables that can be adjusted are the RF pulse length and the klystron peak power. Figure 1 gives the calculated variation of S as a function of RF pulse length.³

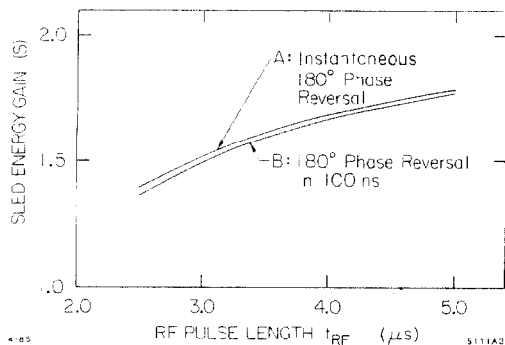


Fig. 1. Calculated SLED energy gain S as a function of RF pulse length (A: assuming instantaneous 180° switching time; B: assuming 180° switching with 100 nsec dead time).

What is the actual energy requirement per girder? A complete account of the energy budget is beyond the scope of this paper⁴ but broadly, the following factors enter into the calculation:

1. The e^\pm bunches are ejected from the damping rings into the second sector of the linac at an energy of 1.21 GeV. From there to Sector 30, there are 230 klystron stations of which 225 are assumed to be on-line at any given time. The energy of the bunches at the end of the linac must be 51.5 GeV because they lose 1.5 GeV through synchrotron radiation in the arcs.

2. Single-bunch beam loading compensation for $5 \times 10^{10} e^+$ or e^- reduces the peak energy by 2.5 GeV, and the energy removed by the first bunch reduces the energy of the second bunch by 0.85 GeV.
3. Special phase offsets to produce Landau damping further reduce the energy by 3%, and all other effects due to imperfections in timing, phasing, special sections, etc., are assumed to cost another 3%.

Taking all these factors into account, the no-load energy V to be delivered by each of the 225 stations is 253 MeV.

Three solutions were considered. The first one was to eliminate the SLED cavities altogether. In this case, it can be seen by substitution into Eq. (1), letting $S = 1$, that the power needed out of the klystron is 160 MW. Such a klystron needs to produce only a 1 μ sec RF pulse to match the 0.83 μ sec accelerator filling time since we are interested in accelerating only three bunches, roughly 120 nsec apart. Two prototype klystrons of this kind were actually built and tested⁵: the first one with a single-gap output gave 120 MW, the second one with a double-gap output gave 150 MW, both at 475 kV. While promising, this avenue has not been pursued further because of increased klystron and modulator size and cost, and because the 1 μ sec pulse would be too short for experiments other than the SLC. The second approach under consideration was to use two of the existing XK-5 klystrons (34 MW peak, 30 kW average, 265 kV) in parallel. Referring again to Fig. 1, we see that by combining the powers of two such klystrons driven by a single modulator with a pulse length of 3.5 μ sec, the SLED gain S is 1.59 and the energy V becomes 262 MeV, in excess of the 253 MeV required. This solution was studied and tested in enough detail to be kept as a contingency but it was not adopted because it would have doubled the number of klystrons on the linac and increased its operational complexity considerably. The third approach, which has been adopted as the most desirable solution, makes use of a new klystron of power intermediate between the two tubes discussed above. The required energy can be reached with this klystron operating at 50 MW peak and a 5 μ sec pulse length which yields a SLED gain S of 1.77.

Klystrons

The general design parameters for the new klystron are shown in Table 1. This klystron⁶ is designated as Model 5045 because its nominal peak power is 50 MW and its nominal average power for a 5 μ sec pulse length and 180 pps is 45 kW. The tube, in contrast to earlier SLAC models, is focused by an electromagnet. The cathode, which has a required peak current density of 6.8 A/cm², is of the dispenser type. Although no experience exists, the model presently used meets this specification at a low enough temperature that a cathode life of 20,000 hours may be projected. Figure 2 is a photograph of the klystron. It has an overall length of 1.7 m and uses six cavities. It has a coaxial input line and a single waveguide output which splits into two arms with two windows in parallel, beyond which the power is recombined into a single output. The

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

Table 1. 5045 Klystron Parameters

Operating voltage (kV)	315
Perveance (10^{-6})	2.0
Peak beam current (A)	354
Frequency (MHz)	2856
Power output (MW)	50
Repetition rate (pps)	180
Efficiency	0.45
Gain (dB)	50
RF pulse width (μ sec)	5.0
Effective beam pulse width (μ sec)	6.0
Cathode type	Dispenser
Focusing magnet	Electromagnet

peak power output as a function of operating voltage is plotted in Fig. 3 for two 5045 klystrons. Note that at 320 kV an output of 51 MW was observed on both tubes. The drive power requirement was in the 400 to 600 W range. In parallel with klystron production, we are proceeding with an R&D program to work on some of the tube characteristics where technical difficulties have been encountered. This work includes improved computer codes to predict klystron performance, investigation of tube instability, breakdown, and RF windows.

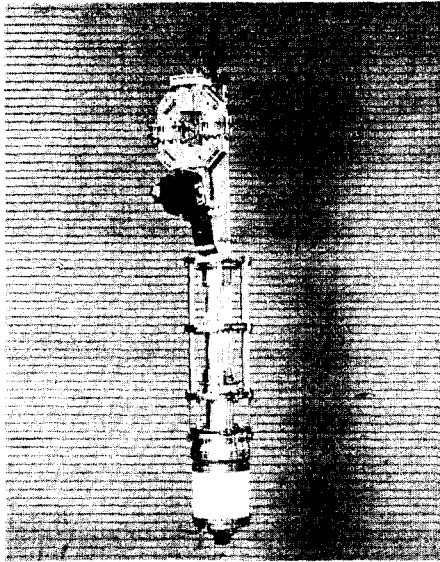


Fig. 2. 5045 klystron with two parallel output windows.

Tube instability which manifests itself as amplitude and phase modulation in the RF output pulse is being studied by varying various parameters such as RF drive, focusing field, heater current, perveance and output cavity external Q . Breakdown in the gun region has already been greatly reduced by careful selection of electrode materials, extensive polishing and careful conditioning. The present RF windows are $\frac{1}{8}$ -inch Al_2O_3 disks brazed into copper sleeves and coated on both sides with titanium nitride for multipactor suppression and charge removal. Window fracture or puncture has been reduced substantially by using two windows in parallel as described earlier. Despite this, occasional window heating and fracture, particularly at 180 pps, are still being observed. The amount of heat dissipation in these cases seems to be higher than can be explained by simple RF losses, leading to various hypothe-

ses, e.g., electron bombardment by an electron wind,⁸ multipactor, poor titanium nitride coating resulting in high conduction losses or charging up of the ceramic surface, poor brazing and various uncontrolled chemical surface reactions. Several other approaches are being studied such as thicker windows ($\lambda/2$) within longer pill-boxes, thin BeO windows (for better heat conduction) and higher density Al_2O_3 .

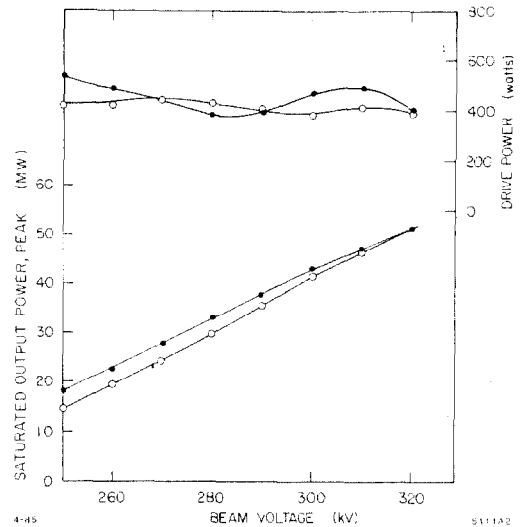


Fig. 3. Performance of two 5045 klystrons as a function of beam voltage (180 pps, 5 μ sec pulse length, fixed magnetic field optimized for 320 kV).

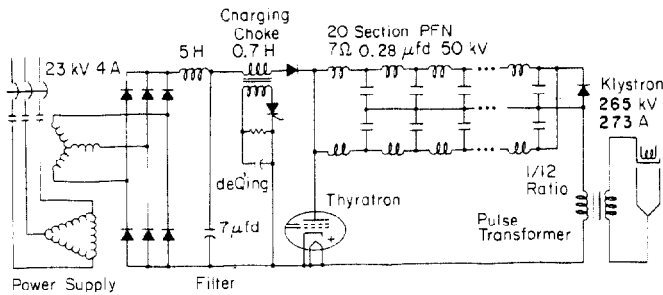
Completion of the SLC project requires that 230 new klystrons be installed and operating on the linear accelerator by October 1986. Since there was insufficient time to subcontract any fraction of this klystron production to outside vendors, SLAC has developed a large facility to fabricate these tubes in-house. The only sub-assemblies that are procured outside are the cathodes. Our material procurements, which have included 15 tons of 304L vacuum melted stainless steel, 50 tons of OFE copper and 2.5 tons of cupronickel, have been subjected to stringent quality controls (4800 metallographic samples taken to date). Close to 10% of the materials received did not meet specifications and were rejected. The klystrons are made out of carefully tested sub-assemblies. When completed, they are placed in a bake-out station, evacuated, leak tested and monitored by a residual gas analyzer. The outer side of the tube is enclosed in a large stainless steel bell jar and baked at two stages, first at 500-600° C, and then at 400° C. Our material control program is paying off handsomely in that the necessary bake-out time for the tubes has dropped from 15.2 days to 7.2 days, thereby reducing the number of bake-out stations required and saving capital equipment costs. The current production capability is four klystrons per week. This rate will be increased to five tubes per week in the next few months.

Modulators

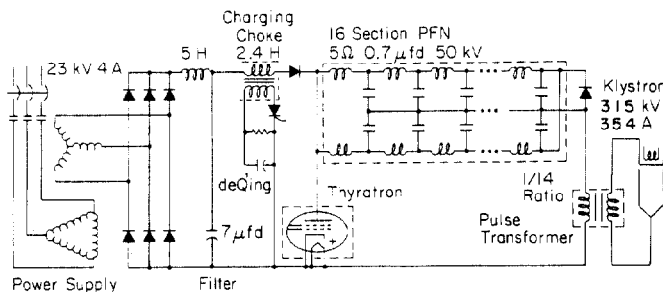
The modulator upgrade program consists of rebuilding the existing SLAC modulators and reusing as many parts as possi-

ble to accommodate the new requirements. The two stages of the upgrade, first at 120 pps and later at 180 pps, are shown in Fig. 4.

(a) EXISTING MODULATOR (360 pps) FOR XK-5 KLYSTRON



(b) UPGRADED MODULATOR (120 pps) FOR 5045 KLYSTRON



(c) UPGRADED MODULATOR (180 pps) FOR 5045 KLYSTRON

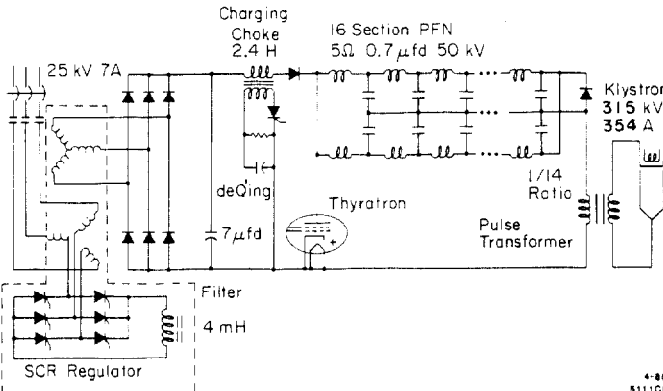


Fig. 4. Modulator upgrade program. Dashed boxes indicate components or sub-systems being upgraded or replaced at a given stage.

The 18% increase in klystron voltage and the factor of 2.1 increase in pulse transformer volt-seconds results in the requirement for a new pulse transformer and tank. The new pulse transformer has a 14-to-1 turns ratio, maintains the same primary voltage as the pulse transformer for the XK-5 tube, the same peak volts per turn of 3.75 kV, and allows for increasing the klystron voltage up to 350 kV. The design is essentially the same as that of the earlier transformer, with two parallel secondary windings with core bias. The klystron heater which is powered through the two secondaries increases from 300 W up to 1000 W, requiring a new heater transformer and heater circuit. The higher secondary voltage results in a modification of the capacitive voltage divider to accommodate the higher pulsed voltage. The new tanks with pulse transformers and heater transformers are being assembled at SLAC.

The increase in modulator pulse length to slightly over 5 μ sec and peak power to 112 MW results in a pulsed energy increase by a factor of 2.8 over the earlier modulator. The 20 capacitors (each 0.014 μ fd) in the pulse-forming network (PFN) are being replaced by 16 capacitors (each 0.042 μ fd). The charging choke is being increased from 0.7 to 2.4 H. The original Tung Sol/ITT CH-1191 thyatron was first assumed to be adequate for operation at 50 kV, 5000 A, 5.3 μ sec, 6 A average, but turned out to have a high fault rate. Several alternate solutions are being tried, including an English Electric Valve 1536A, two CH-1191 in parallel, one CH-1191 modified by the Omni Wave Corp. or a new upgraded ITT thyatron.

The average power required for the modulators at 5 μ sec and 120 pps is essentially the same as that of the earlier modulators at 2.5 μ sec and 360 pps. Upgrading the modulators for 180 pps operation, which will probably take place at a later date, will require a 32% increase in average power. For this, the rectifier transformers, filter inductors and switch gear will need replacement. The present variable voltage transformer system will be replaced with a standard 480 V distribution with individual breaker feeds. Each modulator will have a primary SCR phase control rectifier with primary filter inductor. The phase controller will provide for voltage regulation in conjunction with an active deQ'ing to implement a wide range of voltage control.

As this paper is being written, close to 70 new klystrons have been accepted for installation and up to 16 full stations are in operation at 60 pps on the accelerator. Elaborate tests are under way to monitor the performance of all the RF, electric, vacuum and cooling water systems and components.

Acknowledgements

The authors are indebted to a large number of people in the Technical and SLC Divisions of SLAC who are working very hard to make the SLC energy upgrade program a reality. In particular, they would like to thank R. S. Callin, R. A. Ecken, W. R. Fowkes, E. Garwin, E. W. Hoyt, T. W. Johnston and T. G. Lee for major contributions to this work.

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